Lesson 2: Mission: Possible

How Can We Plan an Exploration of Another World?

Lesson Overview

Grade Level
5–8

Duration
Two 45-minute class periods

Essential Question
How can we plan an exploration of another world?

Lesson Summary

Students will understand how to plan a trip to another world in the Solar System. They will begin by discussing the path of a spacecraft traveling between planets, examining the journey from the Earth to Mars as an example. In Activity 1, students will determine the pros and cons for different ways we can explore another world, either by observing from the Earth or by sending a spacecraft to fly by, orbit, or land on the world. In Activity 2, the students will plan for a mission to explore another world in the Solar System. They will come to understand that what scientists want to learn about an object determines how they plan the mission, but real-life constraints such as cost, fuel and time, determine what they actually can accomplish.

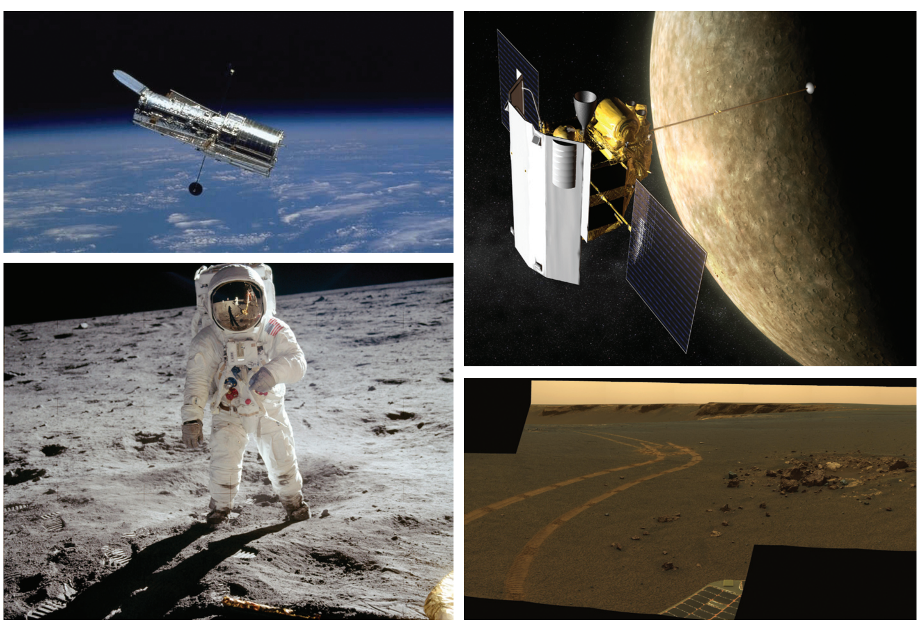


Figure 1. How do we explore other worlds in the Solar System? Depending on the goals and the constraints of the mission, the exploration can be done through observations with telescopes on (or near) the Earth (e.g., Hubble Space Telescope, top left), by having robotic spacecraft making remote measurements by flying by or orbiting the world (e.g., MESSENGER mission to Mercury, top right), landing on the target world (e.g., Martian rovers, which took photographs of the surface of Mars including its own tracks across the landscape, bottom right), or by sending humans to do the exploration (e.g., Apollo missions to the Moon, bottom left.) (Picture credits: NASA, (http://hubblesite.org/gallery/spacecraft/06/;NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/artists_impression.html; NASA Project Apollo Archive/Apollo Image Gallery, scanned by Kipp Teague, AS11-40-5903; http://www.apolloarchive.com/apollo_gallery.html: NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)

This lesson was developed by the National Center for Earth and Space Science Education.

Objectives

Students will be able to do the following:

- Consider the relationship between the locations of the planets as they move around the Sun.
- Make multi-sensory observations.
- Gather data.
- Demonstrate an understanding of real-life constraints on spacecraft missions.

Concepts

- There are many ways to study and plan a mission to a planet.
- There can be more than one solution to a problem.
- Real-life constraints such as cost, fuel and time determine what can actually be learned about another world.

MESSENGER Mission Connection

The MESSENGER spacecraft is a one of NASA's Discovery missions, which are meant to do a lot of science within a limited budget. However, even with the relatively inexpensive mission, scientists and engineers were able to create an orbiting spacecraft that will tell us more about Mercury than we knew from the only previous mission to Mercury (Mariner 10) and all ground-based observations combined.

Standards & Benchmarks

National Science Education Standards

Standard A2: Understandings about scientific inquiry

- Different kinds of questions suggest different kinds of scientific investigations. Some investigations involve observing and describing objects, organisms, or events; some involve collecting specimens; some involve experiments; some involve seeking more information; some involve discovery of new objects and phenomena; and some involve making models.
- Mathematics is important in all aspects of scientific inquiry.
- Scientific investigations sometimes result in new ideas and phenomena for study, generate new methods or procedures for an investigation, or develop new technologies to improve the collection of data. All of these results can lead to new investigations.

AAAS Benchmarks for Science Literacy

Benchmark 3B1:

- Design usually requires taking constraints into account. Some constraints, such as gravity or the properties of the materials to be used, are unavoidable. Other constraints, including economic, political, social, ethical, and aesthetic ones, limit choices.

Benchmark 2B1:

- Mathematics is helpful in almost every kind of human endeavor—from laying bricks to prescribing medicine or drawing a face. In particular, mathematics has contributed to progress in science and technology for thousands of years and still continues to do so.

Science Overview

Before any travel, it is good to plan the trip as carefully as possible. What is the best way to get to a destination? What will you do once you reach your destination? What kind of supplies might you need? How much is the trip going to cost? The same is true when planning for an exploration, and especially when planning for space travel to investigate another world. Careful planning makes the mission more likely to succeed.

When planning an exploration of another world, scientists need to consider what kind of information they want to gather. They need to formulate the scientific goals of the mission, and then figure out what is the best way to meet the goals within their budget. If the study cannot be conducted using ground-based observations or using telescopes located near the Earth in space, they must consider the extra cost of sending a spacecraft to explore the world by flying by, orbiting, or landing on the target world. The exploration gets more complex and expensive as you progress from ground-based observations to a fly-by, an orbital, and a landing spacecraft mission. Most often, the final mission is a compromise between what the scientists want to find out about their target, and what real-world constraints allow.

Observations from Earth

Scientists explored the Universe for thousands of years by using just their unaided eyes to observe phenomena in the sky. While much can be learned about the positions and behavior of the objects in the sky without additional equipment, it is difficult to come to understand the basic nature of the objects observed with just bare eyes. The significant break-through in the exploration of the Universe occurred in about 1608, when the first telescope was constructed. The new tool was soon used by Galileo Galilei to observe objects in the sky no human had ever seen in such detail before; this was the beginning of the era of detailed astronomical observations.

Over the last few hundred years, telescopes have become more advanced not only in the way they are constructed, but also in the way observations are made. At the time of Galileo, astronomers jotted down their observations in notebooks, and the data was only as good as the observer's notes. The development of photographic plates, and, in more recent times, the introduction of even more advanced image capturing and enhancement technologies to astronomy, have made ever more complex observations possible. As a result, the last hundred years has revolutionized our understanding of the Solar System, the rest of the Universe, and our place in it. Today, ground-based telescopes are still the most commonly used tools in observational astronomy, because they are relatively inexpensive to build, maintain, and use, at least when compared with other options. It turns out that the bigger the size of the telescope's lens or mirror, the fainter, the smaller and/or more distant the objects it can

observe. Telescope designers therefore race to make new techniques to build, maintain and use ever bigger telescopes. The largest telescopes in the world today use mirrors of about 10 m (394 inches) in size. There are two telescopes of this size; they are located at the Keck Observatory (Fig. 2) on Mauna Kea, Hawaii, and they can be used either separately or together to enhance the observations even further. The total cost of the Keck telescopes was $231 million to design and build; this includes $48 million for instrumentation (camera systems, etc.) that are mounted on the telescope to make the actual observations. There are plans to build telescopes that have mirrors as big as 30 m (1181 inches) in diameter over the next decade or so.

However, there are limits to ground-based observations. Because the telescopes must see through the Earth's atmosphere, which is constantly moving, the clarity of the observations is decreased. There are computer software packages that can overcome some of these problems, but they cannot remove the effect of the moving atmosphere completely. Another way to alleviate the problem is to build telescopes in areas where the atmosphere is naturally calm, or high up in the mountains, where the light coming from objects in space has less atmosphere to pass through. That is why most of the premier observatory sites today are located in high-altitude locations such as Chile and Hawaii. Still, even the best ground-based observations suffer from some atmospheric effects.

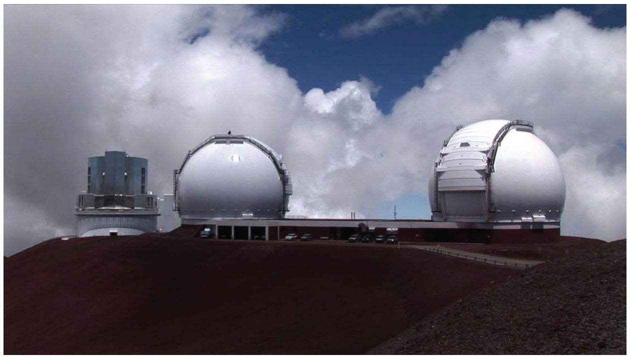


Figure 2. The Keck Observatory in Mauna Kea, Hawaii, includes two telescopes whose 10-meter mirrors are the largest in the world. The telescopes are located inside the domes seen in the figure; the domes protect the telescopes from the environment and are opened for observations. (Picture credit: NASA; http://www.nasa.gov/centers/jpl/images/content/135066main_Keck-9-29-05-browse.jpg)

Observations from Space Near Earth

One way to solve the problem of the atmosphere is to place the telescopes in space. This is a popular approach not only because of the limited seeing from the ground, but also because there are many kinds of light that are blocked by the Earth's atmosphere but are observable by telescopes in space. Ground-based telescopes can observe in the visible, radio and some infrared and ultraviolet light, but only telescopes above the Earth's atmosphere can observe gamma rays, X-rays, and most of infrared and ultraviolet light. As a result, space telescopes have become very popular over the last few years.

Probably the best known space telescope is the Hubble Space Telescope (HST; see Fig. 3), which was placed into orbit around the Earth by the Space Shuttle in 1990. While the size of the HST's

mirror is small (2.4 m; 94 inches) compared with the large ground-based telescopes, the seeing from space is so much better that the observations made by HST have revolutionized many aspects of astronomy. It has taken hundreds of thousands of pictures, observing more than 25,000 astronomical targets. There probably are many new discoveries in store before the end of HST's operational lifetime sometime after 2013. The cost of HST at launch was $1.5 billion, which included the design, building, testing, and launch of the telescope. Four additional Shuttle missions have repaired components of the HST and swapped instruments over the years, with a fifth scheduled in 2008. The cost estimates for the Shuttle missions have ranged from $600 million to $2 billion, increasing the cost of the Hubble Space Telescope significantly. There are many other important space-based observatories; for example, NASA's Great Observatories program includes not only the HST, which studies the Universe using visual, ultraviolet and near-infrared light, but also the Compton Gamma Ray Observatory, Chandra X-Ray Observatory, and the Spitzer Space Telescope, which study the Universe using gamma rays, X-rays and infrared light, respectively.

Besides the costs and the types of light that are observable, one of the main differences between ground-based and space telescopes is the ease of repair. Ground-based telescopes can be repaired much easier than space telescopes. For example, HST has many redundant electronic circuits, but any needed repair involves a repair mission using astronauts on a Shuttle flight. Some space telescopes are on orbits that are not serviceable by the Shuttle, so no repairs are possible for these telescopes. Both ground-based and space telescopes can quickly switch between different kinds of cameras and point to different parts of the sky, but only ground-based telescopes allow an observer to use his or her own instrument packages, if that is necessary for the observation.

Figure 3. Hubble Space Telescope (HST) was placed into orbit around the Earth by the Space Shuttle in 1990. It has taken hundreds of thousands of pictures since then, observing more than 25,000 astronomical targets, and in so doing become probably the most important telescope in the history of astronomy.
(Picture credit: NASA; http://hubble.nasa.gov/hubble/full/img94.jpg)

Robotic Explorations of the Solar System

Almost all of what we know about the Universe beyond the Solar System was discovered through observations on the Earth or in orbit around the Earth. However, much of what we know about our Solar System has been due to observations by spacecraft that have been sent to make close-up

observations of the objects in our planetary system. In fact, we have learned more about the Solar System in the last 50 years using robotic spacecraft than all the previous ground-based observations.

After the launch of Sputnik 1 satellite in 1957 ushered in the Space Age, robotic spacecraft (and in the case of the Moon, human space flight) have been used to study various worlds in the Solar System, with at least one spacecraft visiting each of the seven other planets, some of their moons, as well as a few asteroids and comets. There are spacecraft currently on their way to examine the dwarf planets Ceres and Pluto, and the spacecraft flying by Pluto may also examine at least one of the Kuiper Belt Objects, which are icy worlds beyond the orbit of Neptune discovered in the last few years. Other spacecraft missions are carrying out more detailed observations of the many different types of worlds in the Solar System right now, or are being planned. Depending on the kind of information scientists want to discover, the distance to the object being studied, and budgetary constrains, the robotic spacecraft can be sent on a fly-by, orbital or lander mission.

Fly-By Mission

The simplest way to explore a world close-up is to have a spacecraft fly by the body without going into orbit around it or landing on it. A fly-by can get more detailed information on the object being studied than Earth-based observations. However, the spacecraft can only make useful observations of the world while it is nearby, and depending on the trajectory of the spacecraft, the time for observations may be limited and only a small portion of the object facing the spacecraft as it flies by may be viewable. This means that a fly-by mission requires a lot of planning to optimize the way the data is gathered. Usually, the details of the planned observations—which instrument to use at each moment, where to point the instrument, what kind of data to take, etc.—are stored in a computer program on the spacecraft before the fly-by, and the program begins executing automatically at some distance from the target. The gathered data is then sent back to the Earth for analysis after the fly-by is concluded.

The costs of a robotic flyby mission vary depending on the world that is being explored. Typically the costs involve consideration for the following aspects:

- Designing and building the instruments needed to get the desired science data;
- The power needed to run the spacecraft and its instruments;
- Launching the spacecraft;
- The amount of fuel needed to fly to the world;
- Communications needed between the Earth and the spacecraft;
- The length of the mission.

The basic design and structure of the spacecraft is usually done in concert with designing the instrument suite. The spacecraft, after all, is really just a vehicle to take the instruments to their target, allow the instruments to operate properly in the environment at their target world, and make it possible for gathered data to be returned to Earth for analysis. There is always a tradeoff between the amount and type of science data that is desired and the cost of the instruments to get this data. If a similar mission has been done before, there can be a great cost savings by using the same kind of instruments that were used or developed for that mission. There are also engineering costs associated with incorporating the instrument into the spacecraft, but they are significantly lower. A typical instrument on a spacecraft costs a few million dollars, while the design and construction of the whole spacecraft can vary from a few tens of millions of dollars to $1 billion dollars, depending on the kind of engineering needed to complete the project.

In addition to selecting the instruments, the power needed to operate them must be considered when designing the mission. If the spacecraft is exploring the inner Solar System (the planets Mercury, Venus, or Mars, for example), solar arrays can be used to get power from sunlight. If the mission is to worlds farther out, the spacecraft will need to rely on nuclear energy. The power is in these cases derived from the natural decay of a radioactive isotope, most often plutonium-238. For example, the Voyager 1 and 2, Gaileo, Cassini-Huygens and New Horizons spacecraft use this power source. Future long-duration missions exploring worlds in the outer reaches of the Solar System may need new technology, such as a small nuclear reactor incorporated to the spacecraft.

The cost of launching a spacecraft depends on a number of factors, especially on the size and weight of the spacecraft and amount of fuel aboard. The cost of lifting a spacecraft from the ground to space is about $22,000 per kg ($10,000 per pound); additional costs come from sending the spacecraft toward the target world. The typical cost per launch is around $40 million for spacecraft heading to the inner Solar System and Mars, and roughly $100 million for spacecraft heading to the outer reaches of the Solar System.

The spacecraft carries fuel for course corrections maneuvers that may be necessary to adjust its trajectory toward the world. The spacecraft is usually launched on a trajectory that requires as few course corrections requiring the firing of the spacecraft engines as possible. The typical spacecraft carries a few hundred kilograms/pounds of fuel, at a cost of about $80/kg ($36/lb.) For example, the MESSENGER spacecraft heading to Mercury carried a total of 600 kilograms (1,323 pounds) of fuel at the start of its journey, resulting in a total fuel cost of approximately $48,000. However, this is only the direct cost of the fuel, and does not include the cost of lifting it to the orbit (which is included

in the launch cost above.) For example, in the case of MESSENGER, the cost of lifting the fuel to orbit cost $13.2 million, much more than the actual value of the fuel.

Communications with spacecraft studying other worlds are done using radio waves, which travel through space at the speed of light. As a result, the time between sending a signal to the spacecraft and receiving its response varies from a couple of seconds (for missions exploring the Moon) to several hours (for missions investigating the outer reaches of the Solar System.) This delay makes it necessary for the spacecraft to be able to execute many commands on its own, without direct input from ground control on Earth. Therefore, the computer programs operating robotic spacecraft must be designed carefully. For example, before firing the spacecraft's engines to make a course correction maneuver, a signal is sent from ground control to the spacecraft, which causes the computer to execute a series of commands to complete the necessary operations, but providing additional commands is usually not possible before the maneuver is completed. Communication with spacecraft is done using large radio antennas on Earth, such as NASA's Deep Space Network, a network of three antennas located around the world. The time to use the antennas must be planned in advance and purchased. Typical prices for using these communication facilities range from a few million to a few tens of millions of dollars, depending on the frequency of communications and the amount of data transmitted back to Earth.

The length of the mission increases the cost of the mission, since a longer mission requires not only continued communications with the spacecraft, but also human labor on Earth to monitor and communicate with the spacecraft, as well as analyze the larger amount of data returned by the spacecraft. Mission length depends on many factors, among them the distance to the target world, the way the spacecraft travels there, the power available to operate the spacecraft, and the scientific goals of the mission. The mission also becomes longer if the spacecraft is directed to fly by multiple targets. For example, the Voyager 2 spacecraft flew by Jupiter, Saturn, Uranus and Neptune in the 1970s and 1980s.

Designing a spacecraft mission often involves making compromises with the different aspects of the program to keep the total costs within budget. This may require changes in the spacecraft or instrument design, or in the amount of data that can be returned back to Earth. On the other hand, a very successful spacecraft may also earn an extended mission, which allows the spacecraft to continue its exploration with additional funds even after the nominal mission is completed.

Orbital Mission

While a fly-by mission is the simplest, and therefore the most likely to be successful, spacecraft mission to explore another world, it usually only offers a snapshot of one part of the world. A more complicated mission, but also one that can offer a

more comprehensive science investigation, is an orbital mission, in which the spacecraft goes into an orbit around the target world (see Fig. 4.) The main complication in this kind of mission compared with the fly-by is the orbit insertion maneuver: firing the spacecraft's engines to change the trajectory so that the gravity of the target world can "capture" the spacecraft into an orbit around the object. An orbital mission can obtain more detailed information than a fly-by since it not only will be able to see much more of (if not the entire) world, but it also can spend a longer time making observations.

In addition to the costs described in the context of a fly-by mission, the following additional aspects must be considered for a robotic orbital mission:

- Fuel required for the orbit insertion maneuver and for any orbit correction maneuvers that may be necessary later during the mission;
- Hardware and software engineering necessary to prepare the spacecraft for the orbit insertion maneuver and for orbital operations;
- Additional instruments that may be desired for a more comprehensive science investigation;
- More involved communications with ground control on Earth.

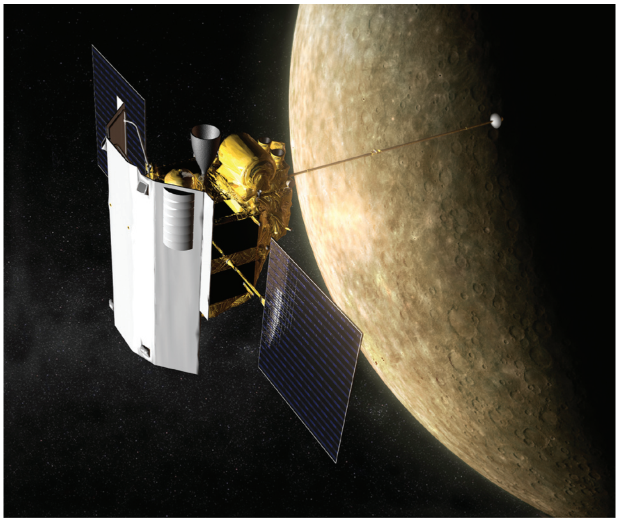


Figure 4. An artist's impression of the MESSENGER spacecraft exploring Mercury. MESSENGER is the first spacecraft to explore the innermost planet in the Solar System since the 1970s, and the first spacecraft ever to investigate the planet from orbit. (Picture credit: NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/artists_impression.html)

Lander Mission

The landing of a spacecraft, or the landing of a probe launched from a fly-by or orbiting spacecraft, to another world entails additional complexity over an orbital mission. In addition to flying to the world, the mission must plan for a safe landing of the probe. In some cases, the probe is designed to just crash on the world and provide as much information as possible before the crash, but in most cases careful planning is required to ensure a soft, safe landing on the target world's surface. Spacecraft can be slowed down during descent toward the surface by firing the engines at precise moments for a pre-determined duration, or by using parachutes if the target has an atmosphere. The spacecraft may also include cushioning (such as air bags) to prevent a jarring landing on the surface. Often, these options are combined to ensure a safe landing. A lander mission is more likely to fail compared with a fly-by or an orbital mission, since

there are more chances for something to go wrong. In fact, about half of all lander missions sent to Mars have failed for one reason or another. On the other hand, a lander mission can provide much more detailed information on the world than the other kinds of missions, often making the higher risk acceptable. A lander can examine the world's surface features close-up and use tools to burrow underground, drill into rocks, or take samples for analysis within the spacecraft. While most landers are stationary, some have been designed to move around the surface, providing detailed information over a larger area (see Fig. 5.)

In addition to the costs of a fly-by mission, as well as those of the orbital mission (if the mission includes an orbiting component), a lander mission involves the following additional cost considerations:

- Fuel to slow down the spacecraft for landing;
- Engineering and additional hardware for landing (e.g., parachute, cushioning);
- Software engineering to prepare the spacecraft for landing;
- Engineering necessary to make communications from the surface back to Earth reliable;
- Additional instruments that may be desired for a more comprehensive science investigation.

Spacecraft Instruments

The types of instruments used by spacecraft exploring other worlds depend on the kind of

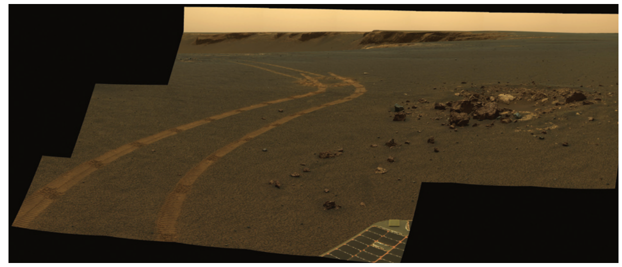


Figure 5. This image taken by the Martian Exploration Rover Opportunity shows not only natural features of the surface of Mars, but also the tracks the rover has left behind. On the lower part of the picture, a section of the rover itself is visible.
(Picture credit: NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)

science the mission designers want to gather about the word. Typically, spacecraft include one or more of the following:

Camera: The basic instruments aboard spacecraft, cameras provide images not only to astonish us with views from another world, but also to provide basic information on the target world for scientists to analyze. The cameras aboard spacecraft are in many ways similar to the digital cameras in wide use today in the way they capture images. Cameras usually have additional tools as part of the image capture system, such as a (small) telescope to take more detailed images, a microscope to allow for detailed analysis of sampled material, or color filters to take images sensitive to different colors, which can then be combined to provide actual color pictures. Depending on how wide a view can be captured, the spacecraft may have a narrow angle (small field of view but can provide more detailed images of a target) or a wide angle (wider field of view, usually less detailed images) camera. A device

with an exceptionally wide field of view is called a panoramic camera. A stereo camera has two lenses that make it possible to take three-dimensional images of a target, in this way mimicking human binocular vision. Cameras may also be sensitive to different kinds of light, producing images using not only visible but infrared light, for example.

Spectrometer: An optical instrument that is used to measure properties of different colors, a spectrometer is often used to provide information on the composition of the object from which the light is coming from. Spectrometers are sensitive to different kinds of light, and the kind of device included in the spacecraft depends on the kind of information the scientists want to gather. Different kinds of light have different energies, and so spectrometers sensitive to various energy ranges can provide different information on the same target. That is why a spacecraft often carries several spectrometers sensitive to different kinds of light, ranging from infrared and visible (low energy) to ultraviolet, x-ray and gamma ray (high energy) spectrometers. Spectrometers can also be built to measure the properties of particle radiation, such as cosmic rays or neutrons, or the properties of geologic or atmospheric samples. Spectrometers are essential in providing information on the composition of the target world's atmosphere, rocks, and soil, as well as providing information on the space environment near the world.

Magnetometer: A magnetometer measures properties of the magnetic field near the spacecraft. The data gathered by a magnetometer can be used to provide information on the target world's magnetic field, the solar wind, and the behavior of the Sun's magnetic field in the space environment near the world.

Laser Altimeter: A laser altimeter uses laser beams bounced off the world being explored to determine the distance to various points on the body. It is commonly used on an orbital mission to map the heights or depths of the geologic features on the world.

Radar: A radar be used like a camera to take images of the target world, but instead of capturing reflected or emitted light, it uses microwaves bounced off the surface of the world. Advanced radar systems can also be used to analyze the properties of the world's atmosphere, or features below the surface.

Seismometer: Just like similar devices on Earth, seismometers can be used on a lander spacecraft to see if there are planetary quakes on the world (e.g., marsquakes or moonquakes.)

Meteorology instrument: To monitor weather on another world, the spacecraft may be equipped with a suite of meteorology instruments to measure the temperature, air pressure, humidity and wind properties, for example.

Geologic exploration tool: For a more comprehensive

analysis of the surface of the world, a lander may include an arm designed to take soil samples from the surface or dig underground. The lander may also be equipped with drills that can bore into rocks for a more detailed analysis of their properties. In these cases, the lander becomes something like a robotic geologist.

Life Experiment Suite: If there is a chance of living beings existing on the target world, a package of laboratory experiments may be included. The experiments may look for life in different ways, such as searching for organic molecules, and chemical signs of microbial feeding or respiration.

The devices above feature the most common types of instruments used by spacecraft exploring other worlds in the Solar System, but there are many other types of tools that that can be included in a spacecraft. More information on the instruments used by past and current spacecraft missions can be found on the various spacecraft mission web pages.

Total Costs of Spacecraft Missions

While the design of the mission becomes more complicated as the type of mission changes from a fly-by to an orbital or a lander mission, there is sufficient variance in the costs discussed above for each type of mission that a lander mission is not always more expensive than a fly-by mission, for example. Many factors can change the costs associated with the mission, and usually the overall budget sets limits on how much science can be done with what kind of mission. For an example of the variation of costs across the worlds explored and the types of missions used, see Table 1.

Table 1: Examples of past and current spacecraft missions exploring other worlds in the Solar System.

World	Mission	Timeline	Type	Total Cost
Mercury	MESSENGER	2004 –	Orbiter	$446 million
Venus	Magellan	1989 – 1994	Orbiter	$680 million
Mars	Mars Express	2003 –	Orbiter	$150 million
	Mars Reconnaissance Orbiter	2005 –	Orbiter	$720 million
	Viking 1 and 2	1975 – 1982	Landers and orbiters	$3.5 billion ($935 million in 1974 dollars)

World	Mission	Timeline	Type	Total Cost
Mars, *continued*	Mars Exploration Rovers (Spirit and Opportunity)	2003 –	Lander / rover	$820 million
	Phoenix Mars	2007 –	Lander	$417 million
Jupiter	Pioneer 10	Fly-by in 1973	Fly-by	$350 million
	Voyager 1	Fly-by in 1979	Fly-by	$905 million[1]
	Galileo	1989 – 2003	Orbiter, atmosphere probe	$1.5 billion
Saturn	Pioneer 11	Fly-by in 1979	Fly-by	$350 million
	Cassini-Huygens	1997 –	Orbiter, lander to Titan	$3.4 billion
Uranus	Voyager 2	Fly-by in 1986	Fly-by	$905 million[1]
Neptune	Voyager 2	Fly-by in 1989	Fly-by	$905 million[1]
Pluto	New Horizons	2006 –	Fly-by	$550 million
Kuiper Belt Object	New Horizons	2006 –	Fly-by	$550 million
Dwarf planet (Ceres); asteroid (Vesta)	Dawn	2007 –	Fly-by	$446 million
Asteroid (433 Eros)	NEAR Shoemaker	1996 – 2001	Fly-by, orbiter, lander	$220.5 million
Comet (9P/Tempel 1)	Deep Impact[2]	2005 –	Fly-by; probe crashed on comet	$240 million
Comet (67 P/ Churyumov-Gerasimenko)	Rosetta	2004 –	Orbiter, lander	$980 million

Notes:

[1] Voyager 1 and 2 costs are the combined cost of the twin spacecraft.

[2] Deep Impact flyby spacecraft was granted an extended mission to study another comet and extrasolar planets under the name EPOXI.

[3] Many of the spacecrafts in the table have flown by multiple targets during their mission, in some cases to perform gravity assist maneuvers designed to boost the spacecraft's speed to reach its ultimate target. For example, Voyager 2 flew by Jupiter, Saturn, Uranus and Neptune, and Cassini-Huygens flew by Venus and Jupiter before arriving at Saturn.

Data from NASA National Space Science Data Center Spacecraft Project Page - http://nssdc.gsfc.nasa.gov/planetary/projects.html - and references therein)

Journey to the Target World

How does a spacecraft travel from the Earth to another planet? Your first guess might be to launch a rocket from the Earth directly toward the planet in a straight line. However, because the planets move in their orbits around the Sun, that method does not work. If the spacecraft heads toward the location where the other planet is when the spacecraft is launched, the planet would have moved along on its orbit by the time the spacecraft would reach the location, and the spacecraft would miss its target. Consider the following analogy. You and a friend are playing catch with a football in a large open field. Your friend runs away from you, and you throw the football to your friend's current location. By the time the football gets there, your friend will be farther away and the football will just fall to the ground. Instead, you need to estimate where your friend will be in a few seconds and throw the ball to that point. If you have guessed correctly, your friend and the football will get to the same point at the same time, and the ball will be caught. You would also notice that the football does not travel in a straight line. This is because once the football leaves your hand, the motion of the ball is controlled principally by the Earth's gravity, which is pulling the ball toward the ground as it flies through the air, causing the ball to fly in an arc.

Now consider sending a spacecraft from the Earth to Mars. When the spacecraft is launched, it does not fly in a straight line, but rather in a curve bending around the Sun. This is because the force of the Sun's gravity is pulling it toward the Sun, just like the same force is pulling the Earth toward the Sun. And just like this causes the Earth to orbit the Sun in an elliptical orbit, the spacecraft at the time it leaves the Earth is on a similar orbit around the Sun. The properties of this initial spacecraft orbit are determined by the launch details, and they can be modified later with course correction or gravity assist maneuvers. If the spacecraft had enough fuel, it could use its engines to overcome the gravitational pull of the Sun and fly in a straight line toward its target. However, to carry enough

fuel, the spacecraft would need to be larger, it would be much heavier and, therefore, it would be much more expensive to launch. This is one of the basic problems to consider when launching a spacecraft. Mission designers want spacecraft to get from the Earth to Mars (or any other planet) using the least amount of fuel. It turns out that the best way to send a spacecraft to Mars from the Earth with using the least amount of fuel is to have the spacecraft travel in a trajectory that is an orbit around the Sun where the orbit's closest approach to the Sun is at the Earth's distance (at launch) and the farthest distance from the Sun the same as Mars's distance (at arrival; see Figure 2.) In this case, the spacecraft does not need to use any fuel while traveling from one planet to the other after being set on the transfer orbit: the spacecraft can cruise through space toward its target.

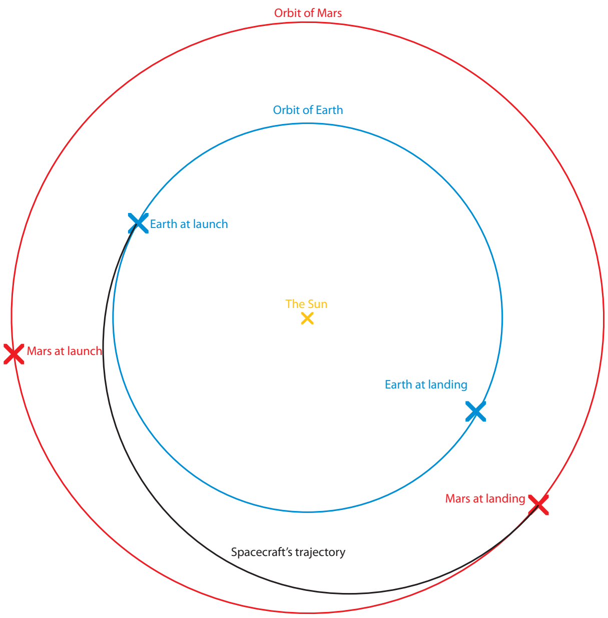


Figure 6. The trajectory of a spacecraft traveling from the Earth to Mars.

Mission Length and Gravity Assists

How long does it take to go from Earth to different places in our Solar System? There were six landings on the Moon during the Apollo era (Apollo 11, 12, 14, 15, 16, 17 in 1969-1972.) It took just over 3 days for the spacecraft to get to the Moon. For travel estimates to other worlds further away, let's assume that a spacecraft is flying at 11.2 kilometers per second (25,000 miles/hour); this is the escape velocity from the Earth; that is, the speed which an object (such as a spacecraft) needs to have to overcome the gravitational pull of the Earth and travel into space. We can now calculate that at this speed, it takes 95 days to travel to Mercury, 43 days to Venus, 81 days to Mars, 2 years to Jupiter, and 16 years to Pluto! Note that the times are just a quick calculation based on the differences in the average distances from the Sun between the world and the Earth, and does not include the more realistic curved trajectory, so the actual trip would take longer at this speed (or faster, if traveling at a faster speed.) However, it provides a good idea of the long travel times to the different worlds in the Solar System.

One way to shorten the travel time is to use more fuel to boost the speed of the spacecraft. However, extra fuel raises the cost of the mission significantly and is rarely worth the cost. Another way to boost the speed without using more fuel is through a method known as gravity assist where a spacecraft can use a planet's gravity to make a spacecraft travel faster and change its direction in

a similar way as a tennis ball thrown at a moving train causes the ball to change direction and speed when bouncing off the train. Using this method can change the speed significantly. For example, the New Horizons spacecraft, launched in 2006, left the Earth at a speed of 16 km/s (36,000 mph.) After flying by Jupiter in 2006, the spacecraft sped up to the speed of 23 km/s (51,000 mph) relative to the Sun. As a result, New Horizons will reach Pluto in 2015, only 9 years after launch. In some cases, a mission might not be even possible without gravity assist maneuvers. For example, without the complicated gravity assist trajectory, the MESSENGER spacecraft would not be able to go into orbit around Mercury. In this case, the complicated trajectory actually increases the travel time, but the requirement to perform an orbital mission makes the extra travel time acceptable.

Human Exploration versus Robotic Missions

Space is a dangerous environment for humans to operate, with hazards ranging from airless vacuum to temperatures that are either scorching hot or freezing cold, depending on whether one is in sunlight or in shade, or close to or far away from the Sun. As a result, humankind has never sent astronauts anywhere other than the orbit around the Earth and to our Moon, and no human has been on the Moon since the Apollo 17 crew returned from their three-day visit in 1972. There are plans to build a permanent settlement on the Moon, and send humans even farther away to Mars in the next few decades, but these kinds of missions require extensive planning and are very expensive. This is due to many reasons. The mission must be self-sufficient all the way to the target world and back; astronauts cannot depend on getting more supplies from Earth if they are far away. For example, establishing a settlement on the Moon or Mars would require that the astronauts grow their own food and have a system to recycle water. In addition, they would have to have equipment to generate oxygen and remove carbon dioxide from the air. They may also need to produce fuel in situ, making locating and securing resources on the target world necessary. Additional thought must be given to secure the health of astronauts in other ways, from combating muscle weakness caused by lower gravity to making sure the dangerous forms of radiation coming from the Sun and elsewhere in the Universe does not cause severe harm to the astronauts. On Earth, we are protected from this harmful radiation by our atmosphere, but the astronauts would not have this protection on a long journey through space, or while on a world without as substantial an atmosphere as the Earth. Astronauts aboard the International Space Station are making experiments to determine how much radiation is dangerous, and what are the best ways to protect against it. While designing robotic spacecraft missions require taking into account many of the same issues (cold and/or hot temperatures, radiation, vacuum), the concern is nowhere near on the same level as it would be

for humans performing the same functions. As a result, robotic exploration of the Solar System remains much more cost-effective than human spaceflight.

Proposing Exploration of Other Worlds

An exploration of another world typically begins with a proposal to funding agency (such as NASA) that provides details for the proposed mission. The science team must explain why their target is worth studying, identify science goals, and explain how the goals can be met with their particular mission. A detailed budget for each aspect of the mission must be provided, and the total budget must be within specified limits. The proposal must also consider the risks associated with the mission and estimate how likely it is to succeed. Often, the proposing team has to modify their initial idea for the mission based on budgetary constraints. Sometimes science goals may have to be scoped down, or some investigations may have to be abandoned to keep the proposal within constrains. For example, NASA Discovery Program allows scientists to propose highly focused planetary science investigations. The program solicits proposals from the planetary science community every so often, and after careful review of all received proposals, the winning missions are announced. The selected missions are cost-capped; that is, the mission teams are given a maximum allowed budget within which they must plan the mission, construct the spacecraft, launch it, monitor its journey, and receive and analyze the data. A lot of work goes into making a winning proposal, but once selected, the mission design team can use the proposal as a blueprint to guide their mission to a successful completion.

Lesson Plan

Warm-Up & Pre-Assessment

1. Make an overhead transparency of each of the three Earth and Mars Orbit Transparencies found in the back of the lesson.

2. Have students share familiar experiences that require reacting to a moving target. Examples might be passing a football, catching a fly ball, driving vehicles to avoid being hit, or playing dodge ball. Lead students to discuss the how and why of the necessary movements to complete the tasks.

3. Display the first transparency with the locations of the Earth and Mars. Ask students to imagine that NASA wants to launch a spacecraft from the Earth to Mars, and it will take about six months to get there. What would happen if they aimed directly to where Mars is at that moment? *(Desired answer: Mars would have moved on its orbit and the spacecraft would miss it completely!)*

4. Remind students how planets move in their orbits; planets closer to the Sun move in their orbits faster than those farther away from the Sun. Ask students where the Earth will be when the spacecraft lands on Mars, if the journey takes six months. *(Desired answer: since Earth takes one year to orbit the Sun, it will be exactly on the other side of the Sun in six months.)* Make a dot on the transparency where Earth would be in six months. Ask students where Mars would be in its orbit. *(Desired answer: since Mars is slower in its orbit, it will not be on the other side of its orbit, and would not have moved as far as the Earth had moved.)* Put up the second Mars and Earth Orbit Transparency with the locations of Earth and Mars six months later.

5. Ask students to imagine the trajectory (path) of the spacecraft as it leaves Earth and meets up with Mars six months later. Have a discussion about what the path may look like.

Materials

Per class:

- ▼ Earth and Mars Orbit Transparency 1, 2, 3

Teaching Tip

You can make class copies of the second transparency and have students draw on their copy their guess of the trajectory rather than leaving it an open discussion.

6. Place the third transparency on top of the second, and line up the transparencies so that students can see the trajectory of the spacecraft. Discuss why it would be very difficult to have the spacecraft travel in a straight line from the Earth to Mars *(Desired answer: to travel in a straight line, the spacecraft would have to fight the gravitational pull of the Sun, which tries to make the spacecraft move on a curved orbit around the Sun, all the way to Mars, while this trajectory allows the spacecraft to cruise most of its journey without using additional fuel. It is more energy-efficient and, therefore, more fuel- and cost-efficient, to use this kind of trajectory. See the* Science Overview *for a more detailed discussion.)*

7. Discuss with the students issues that scientists and engineers have to consider when planning a robotic spacecraft exploration of another world, such as what they want to learn of the world, how to travel to the world, whether to land on the world, or just observe it from a distance, how to send data back to Earth, etc.

Activity 1: Strange New Planet

In this activity, students explore the advantages and disadvantages of different kinds of explorations of another world, such as Earth-based observations, or fly-by, orbital, and lander missions to the world. Students use an object such as a plastic ball or round fruit (cantaloupe, etc.) to represent a planet, and decorate it with stickers to simulate landforms, create clouds using cotton and glue, carve channels, place moons around it, apply scents, etc. They simulate each of the four missions and list the strengths and weaknesses of each. They also discuss the advantages and disadvantages of planning a human spaceflight versus a robotic spacecraft mission.

Materials

Per class:

- Roll of masking tape
- Yard stick
- Stopwatch or clock to measure time

Per group of 3 or 4 students:

- Plastic ball, Styrofoam© ball, or round fruit (cantaloupe, pumpkin, orange, etc.)
- Modeling clay, Playdoh©
- Vinegar, perfume, or other scents
- Small stickers, sequins, candy, marbles; anything small and interesting
- A few cotton balls
- A few toothpicks
- Glue (if needed)
- Towel or a large sheet of opaque paper (to drape over the model planets)
- Push-pin
- Pen, pencil, or marker
- Sheet of colored cellophane; large enough to cover the model planet (optional)
- Index card
- Knife (optional)

Preparation

1. This activity has students create their own planets. However, you can also create the planets for the students and place them on a desk in the back of the room, covered with a towel before students arrive, so that the students cannot see their target planets before they start making their observations.
2. Make one copy of Student Worksheet 1 per student.
3. Gather group materials to pass out or lay out materials for groups to take as needed.
4. Divide students into groups of three or four.
5. Pair up each group with another. Each group will study their partner team's planet.

Procedures

A. Class discussion

1. Ask the class to describe planet Earth. What are some of its characteristic features? How does the Moon look different from the Earth? What do they know about the Moon by just looking at it? How would their observations change if they got closer to the Moon? If they landed on it?
2. Ask the students to come up with different ways they can explore another planet in the Solar System. Make sure the students come up with all the mission possibilities discussed in this activity.

3. Pass out Student Worksheet 1. Explain that the groups will explore the differences between the various ways to explore another planet.

B. Creating a model planet

1. Have each group choose an object such as a plastic ball or fruit (cantaloupe, etc.) that allows for multi-sensory observations. Instruct the students to decorate the object with stickers, toothpicks, scents, etc., to make the object interesting to observe. Some of the materials should be placed discreetly so that they are not obvious upon distant or brief inspection. Some suggestions for features are:
   - Carve channels with a toothpick or a knife
   - Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms)
   - Apply scent sparingly to a small area
   - Use sheets of different color cellophane to wrap up the model planet (to represent different kinds of atmosphere)
   - Create clouds by using cotton and glue
   - Attach a toothpick with a piece of modeling clay at the end (to represent a moon)
2. Make sure students record on Student Worksheet 1 what each feature is and what it represents in their model planet. Their partner team will explore the planet later, and there needs to be a record of what the features are versus what the other team sees.
3. When teams are finished, place the model planets on a desk in one side of the room. Make sure the students place an index card next to each planet identifying the team whose model it is. Cover each model planet with a towel (or a large sheet of opaque paper.)
4. Hand out to the students their Viewers – paper towel rolls or rolled-up sheets of paper.

Materials

Per student:

- ▼ Student Worksheet 1
- ▼ Paper towel roll or a sheet of letter-size paper rolled up (to be used as the Viewer)
- ▼ 5″x5″ square of clear cellophane
- ▼ 6″ piece of tape or a rubber band

C. Mission 1: Earth-based observations (simulating observations made from observatories on the Earth or with space telescopes near the Earth)

1. Have students gather by teams in the opposite side of the room from where the model planets are located. This space will act as Mission Control for each team.
2. If you want to include a representation of the Earth's atmosphere, you can have the students crumple up a piece of clear cellophane, then straighten it out and place it on the end of their Viewers, taped or held in place by a rubber band. This helps to simulate the variation that occurs when viewing objects through the Earth's atmosphere. You can also leave out the piece of cellophane, in which case the observations would be similar to those made by space telescopes near the Earth.
3. Uncover the model planets. Have the teams observe the model planet of their partner team using their Viewers for two minutes. Cover the model planets with the towels.
4. Have the teams discuss and record their observations in Student Worksheet 1. At this point, most of the observations will be visual and will include color, shape, texture, and position. Teams should also discuss and write down questions to be explored in future missions to the planet before moving on to the next section.

D. Mission 2: Fly-by

1. Use masking tape to mark a distance of five feet from the desk holding the model planets.
2. Partially uncover the model planets so that one side of the planet is in sight, but the rest is still covered by the towel.

2\. Have the teams quickly walk by their target planet and use their Viewers to make their observations. Make sure no-one approaches the planet closer than the distance of five feet marked on the floor.

3\. Replace the towels over the model planets.

4\. Have teams reconvene at their Mission Control locations to record and discuss their fly-by observations. The teams should also discuss what they will be looking for on their orbital mission.

E. Mission 3: Orbiter

1. Use masking tape to mark a distance of two feet from the desk holding the model planets all around the table. If the desk is large, you may want to move the planets to individual desks to make sure all sides of the target planets can be observed from the distance of about two feet.

2. Uncover the model planets.

3. Give each team two minutes to orbit (circle) their target planet at a distance of two feet and look at the features on the planet through their Viewer. Remind the students that they have to move around their target planet the whole time; they cannot stop and look closer at any point. Have the students reconvene at their Mission Control to record and discuss their observations. The teams should also develop a plan for their landing expedition onto the planet's surface. Plans should include the landing spot and features to be examined.

F. Mission 4: Lander

1. Remove the cellophane carefully from the model planet, if it was used to simulate atmosphere. Have the teams mark their landing sites on their target planets with a push-pin (or masking tape if the model planet will not accommodate a push-pin.) Have the team place their Viewer around the push-pin and draw a circle on the model planet's surface around the Viewer. Have the teams remove the Viewer. The circle marks the maximum area around the landing site which can be explored with this mission. Remind the students that they are not to make any observations of features beyond the circle.

2. Have the team members observe the area around the landing site close-up for five minutes.

3. Have students reconvene at their Mission Control to record and discuss their observations. The teams should also discuss additional features they might want to investigate with a follow-up mission.

Discussion & Reflection

1. Have students compare their observations made through different methods with the list of features placed on the model planet by their group's partner team. Did they see all features with all methods? Were there any they did not observe at all?

2. Discuss with the students, and make a class list, of the pros and cons of each type of exploration. Your table might look something like the following:

Mission 1: Earth-based observations		Mission 2: Fly-by		Mission 3: Orbiter		Mission 4: Lander	
Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons

3. Discuss with students other differences besides just the kind of observations (the kind of science) one can make with the different missions. Which mission is the easiest to do? Which ones are most likely to require complicated tools and machinery? Which one would be the most likely to succeed? What kinds of hazards could each mission face? Which ones would be most expensive? Etc. (See the *Science Overview* for a more detailed discussion.)

4. Ask the students what kind of mission they would design to explore an object in the Solar System that has never been visited by a spacecraft before. An example could be Pluto, a dwarf planet in the outer parts of the planetary realm of the Solar System (note that the New Horizons spacecraft will fly by Pluto in 2015, so after that Pluto will no longer be a good example.) What do the students know about Pluto already? What would they want to learn with the new mission? Would they want to do a fly-by, orbiter, or a lander mission? The total cost of the fly-by New Horizons mission is $550 million, and it will fly by Pluto nine years after launch. What if the cost of the orbiter mission is two times more, and it takes five

years longer to do it? What if the lander is five times more expensive and takes another five years longer?

5. Discuss with the students how what scientists want to learn about a world determines how a mission is initially planned, but real-world constraints such as available funding can influence mission design significantly. In the next activity, students will plan a mission to explore another world, and they must take into account not only what they want to learn about that other world to decide if it will be a fly-by, an orbiter, or a lander mission, but also consider the costs involved with the different kinds of missions.

6. Ask students what additional problems mission designers might face when planning a human spaceflight mission instead of using robotic spacecraft. *(Desired answers include: equipment and supplies necessary to sustain the life of the astronauts, such as food, water, air, and ways to recycle the resources; shielding from the harsh space environment, especially extreme temperatures and damaging radiation. See the* Science Overview *for more details.)* Discuss with students how these considerations have limited human spaceflight so far to near-Earth space and the Moon, and only robotic spacecraft have journeyed further into space.

Activity 2: Mission Design

Students create a plan for a spacecraft exploration of another world. They will consider different aspects of mission planning, including science goals, engineering constrains, and financial considerations. They have to consider how their exploration would be affected in terms of whether the spacecraft would land, orbit, or just fly by the target. Students will come to understand that what one wants to learn about a world determines how one plans a mission, but real-world constraints such as cost, fuel and time, determine what actually can be accomplished.

Materials

Per group of 3 or 4 students:

- Student Worksheet 2
- Mission Log
- Presentation materials, such as access to PowerPoint or poster board and markers, depending on how you decide to have the groups present their mission proposal

Preparation

1. Students will design a mission to explore another world in the Solar System. You can have students plan their mission without budgetary limits, or you can make this a NASA Discovery Program mission, with a cost cap of $450 million. Examples of past and current Discovery Program missions include Deep Impact to study the comet 9P/Tempel 1, and the MESSENGER mission to Mercury. Placing this restriction on the students' mission makes the design more difficult, because they have to meet their mission goals with limited funding. However, the restriction also makes the decision of which mission to fund more balanced, since all missions would cost roughly the same amount. You can also choose a different cost cap to make longer, more difficult, or more comprehensive missions possible.
2. Make one copy of Student Worksheet and Mission Log (found at the back of the lesson) per group of three or four students.

Procedures

1. Divide students into groups of three or four.
2. Ask each group to choose a world in the Solar System (such as a planet or a moon) that they would like to explore. Tell the students that they will be designing a spacecraft mission to this world using one of the methods they investigated in Activity 1.

3. Pass out the Mission Log from the back of the lesson. It is a description of some of the interesting worlds in the Solar System, and it includes a list of missions that explored these worlds to date. Have groups take a few minutes to look over the Log in order to understand the history of investigating other worlds. They should focus on the world of their choice to understand what is known already of the target based on missions exploring the world so far. Science builds on previous studies, so the students need to create a mission to investigate unknown aspects of the world and not just repeat something that has been done before (unless there is something new that could be learned from a repeat experiment.) Discuss anything that the students find interesting or unusual in the Log.
4. Pass out Student Worksheet 2. Have students follow the instructions to plan a mission to the world of their choice.

Teaching Tips

- You may allow students to conduct more research into what is know about their target world, as well as past missions that have explored the world already, by visiting some of the web sites listed in the Internet Resources & References section.
- In Student Worksheet 2, students are asked to re-think their mission designs due to constraints introduced during the planning process. This is an important part of creating a mission. Encourage students to re-design their mission in order to come up with the most complete and comprehensive mission possible.
- If you have completed the first lesson in the Mission Design Education Module, Exploring Exploring, you can have students form the same groups that they had in that lesson and plan the mission to the world that they chose to investigate there.

Discussion & Reflection

1. Ask students to identify any difficulties in completing this assignment. Ask students to relate these difficulties to real-world constraints. How do they think this relates to what real scientists and engineers go through when designing a mission?

2. Discuss how financial considerations introduced constraints on the students' missions. How do they think space exploration would be different if these constraints did not exist?

3. Have students present their mission proposal to the rest of the class, which can act as a NASA review panel. These kinds of panels are usually charged with reviewing spacecraft mission proposals and selecting one or more missions for funding. In their proposal, the students must include an explanation for why they decided to go with a fly-by, an orbiter, or a lander mission, and they must defend their exploration in terms of the science that can be accomplished, the risk and the total cost of the mission. You can decide in advance how to determine how many of the missions will be funded. The class can vote for which missions they would fund and why. Perhaps you can offer extra credit for those missions that would be selected for funding.

Curriculum Connections

- Technology: Have students explore further the differences between the technology needed for human spaceflight versus robotic spacecraft missions.
- Social Studies: Remind students how financial considerations introduced many constraints on the students' missions. You can take this opportunity to discuss how NASA is funded with federal tax dollars. Have the students research how NASA funding compares with other federal programs. Do the students think the allocation of funds to NASA is appropriate? If NASA were to receive more money to fund more missions to explore other worlds, funding for other programs would have to be reduced, or federal taxes would have to be raised. Discuss how the government must be able to allocate its resources in a reasonable manner, and that there is not an unlimited supply of funding available for any one program or agency.

Closing Discussion

1. Discuss with students how the kinds of questions we want to answer about a specific world may dictate the kind of mission we want to perform. Stress that understanding the similarities and differences between different worlds in the Solar System allows scientists to better understand each object. Being able to use the same kinds of tools to study different worlds can help us design our exploration better.

2. Discuss with students how designing new missions to study other worlds builds on previous explorations, from defining science questions to providing instrument designs that are used to answer those questions.

3. Discuss with students how available technology sets constraints on the kinds of missions that are possible at present time, while sometimes it is possible to develop new technologies to answer a particularly important science questions. Therefore, it is possible for science to drive technology, or for the available technology to define the kind of science that is possible, but the two always go hand-in-hand.

4. Hand out copies of the Mission Information Sheet located at the back of the lesson. Discuss with students how the mission designers had to go through the same kinds of problems the students faced in planning their own missions.

Assessment

4 points

- ▼ Student listed pros and cons for each type of mission in Student Worksheet 1.
- ▼ Student completed Student Worksheet 1.
- ▼ Student used reasoning to support their mission design in Student Worksheet 2.
- ▼ Student presented their idea to the class and used evidence and reasoning to support the mission design.

3 points

- ▼ Three of the four above criteria were met.

2 points

- ▼ Two of the four above criteria were met.

1 point

- ▼ One of the four above criteria was met.

0 points

- ▼ Lesson incomplete.

Internet Resources & References

MESSENGER web site

http://messenger.jhuapl.edu/

American Association for the Advancement of Science, Project 2061, Benchmarks for Science Literacy

http://www.project2061.org/publications/bsl/online/bolintro.htm

National Science Education Standards

http://www.nap.edu/html/nses/

Cassini-Huygens mission

http://saturn.jpl.nasa.gov/home/

Dawn mission

http://dawn.jpl.nasa.gov/

Deep Impact mission

http://deepimpact.umd.edu/

Galileo spacecraft

http://solarsystem.nasa.gov/galileo/

Gravity assists

http://www2.jpl.nasa.gov/basics/grav/primer.html

Hubble Space Telescope

http://hubblesite.org/

Keck Observatory

https://www.keckobservatory.org/

Magellan mission

http://www2.jpl.nasa.gov/magellan/

Mars Express mission

http://www.esa.int/SPECIALS/Mars_Express/

Mars Exploration Rover mission

http://marsrovers.jpl.nasa.gov/home/

NASA's Discovery program

http://discovery.nasa.gov/

NASA's Human Space Fight page

http://spaceflight.nasa.gov/station/

NASA's Mars Exploration Program

http://mpfwww.jpl.nasa.gov/

NASA National Space Science Data Center Spacecraft Project Page

http://nssdc.gsfc.nasa.gov/planetary/projects.html

NASA's Planetary Photojournal

http://photojournal.jpl.nasa.gov

NASA Solar System Exploration

http://solarsystem.nasa.gov/

NEAR-Shoemaker mission

http://near.jhuapl.edu/

New Horizons mission

http://pluto.jhuapl.edu/

Phoenix Mars

http://phoenix.lpl.arizona.edu/

Pioneer 10 and 11 missions

http://www.nasa.gov/centers/ames/missions/archive/pioneer10-11.html

The Nine Planets

http://nineplanets.org/

The Nine Planets - Planetary Science Spacecraft

http://nineplanets.org/spacecraft.html

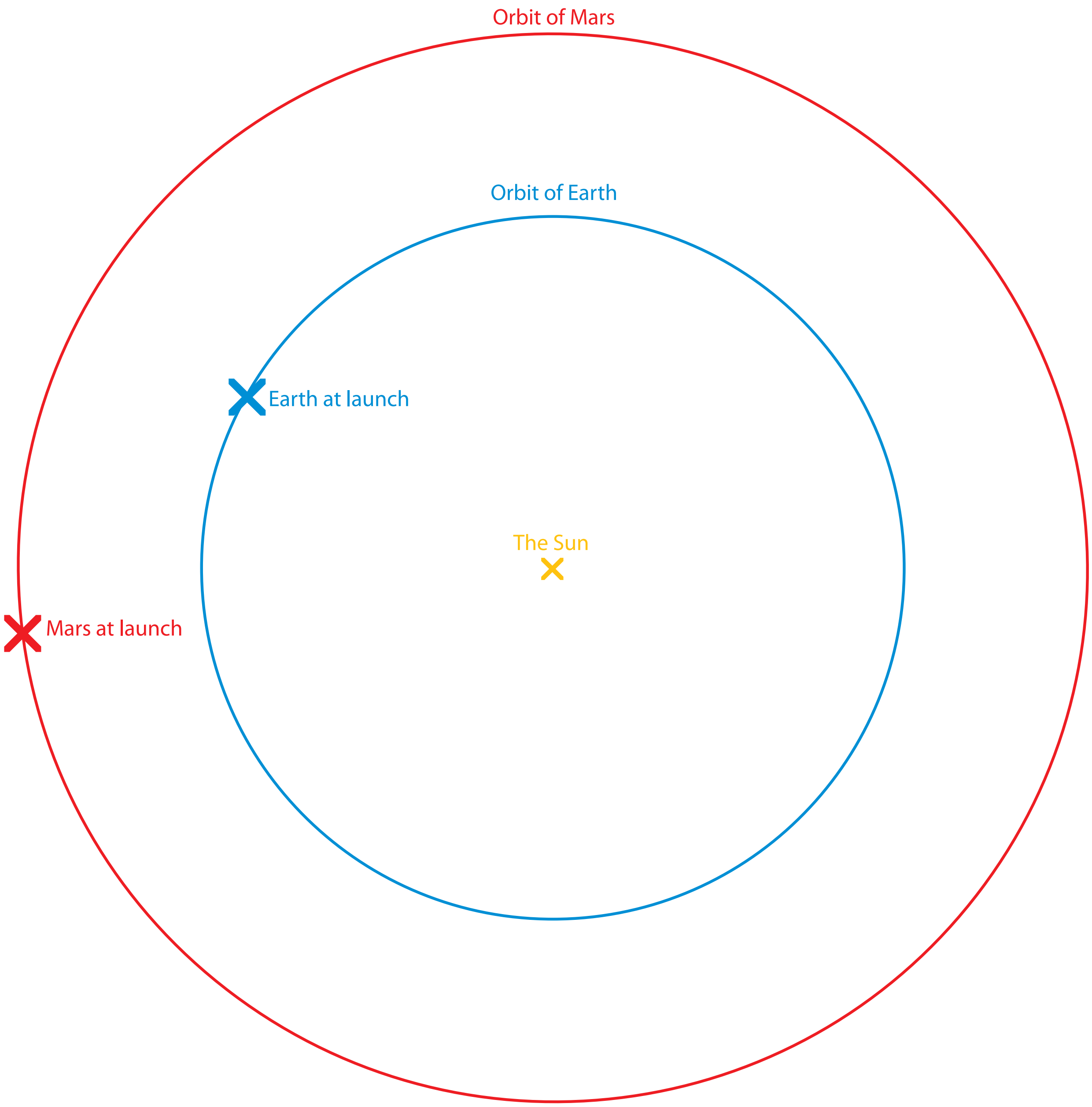
Rosetta mission

http://sci.esa.int/rosetta/

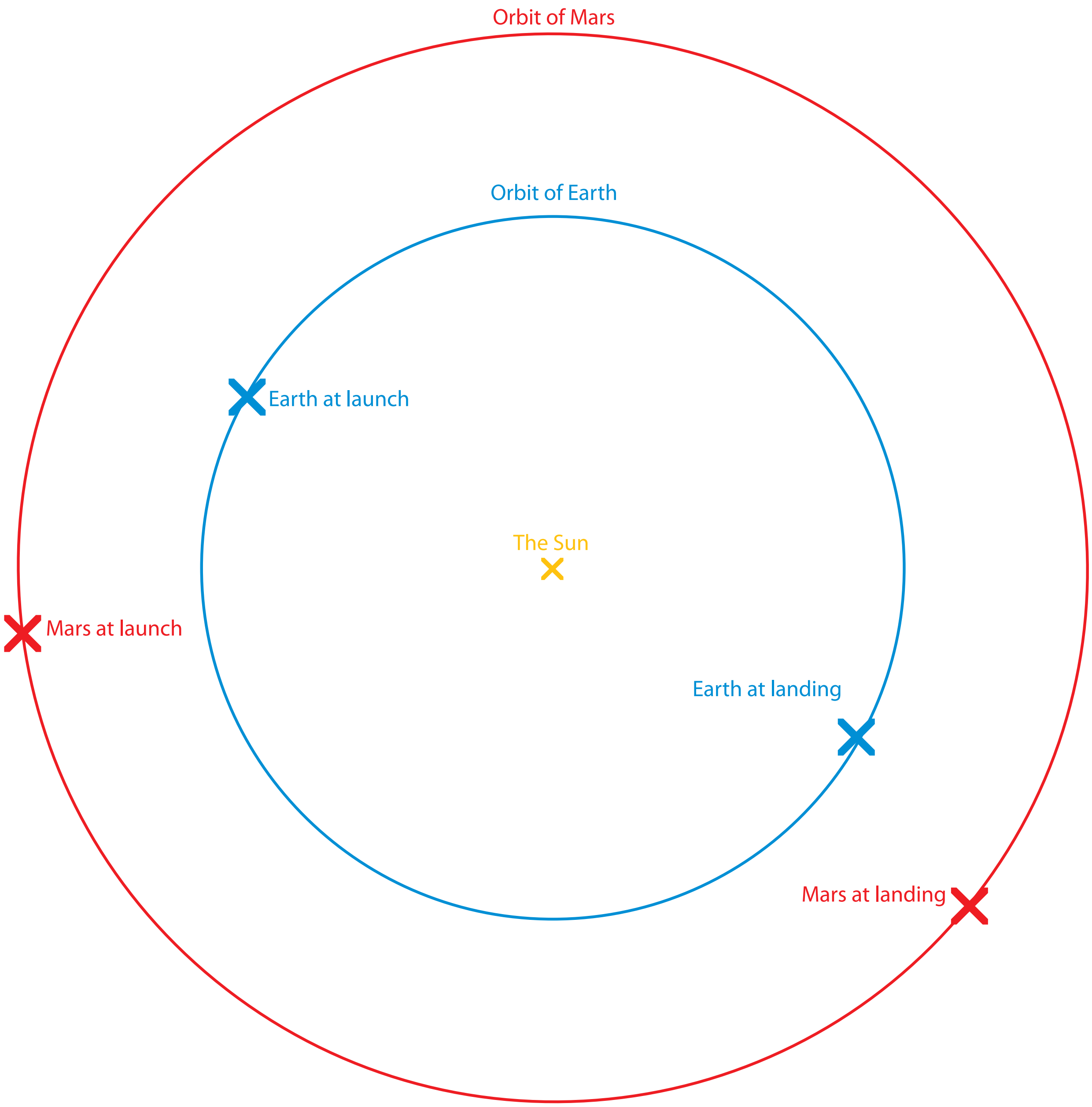
Voyager 1 and 2 missions

http://voyager.jpl.nasa.gov/

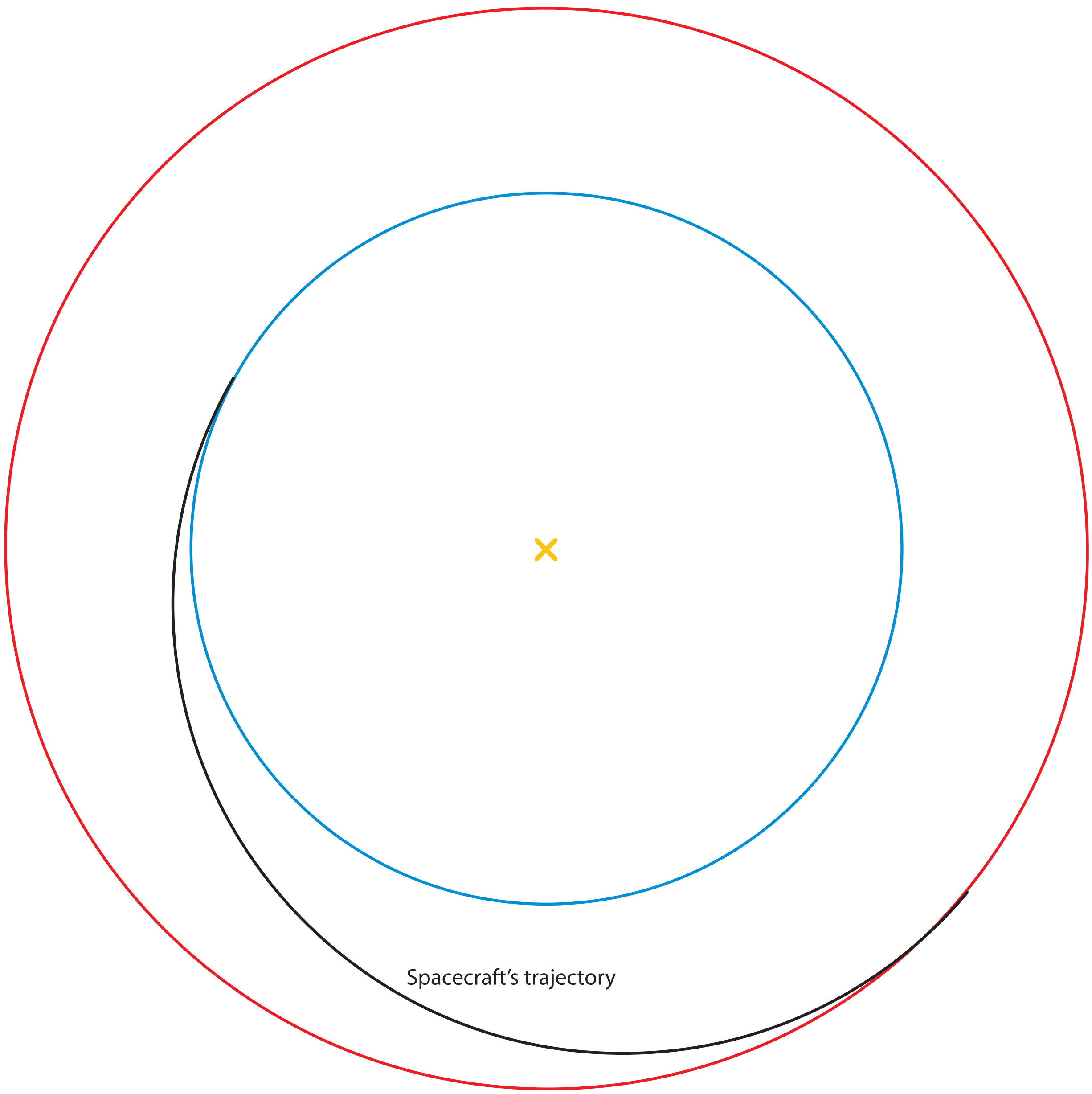
Earth and Mars Orbit Transparency #1



Earth and Mars Orbit Transparency #2

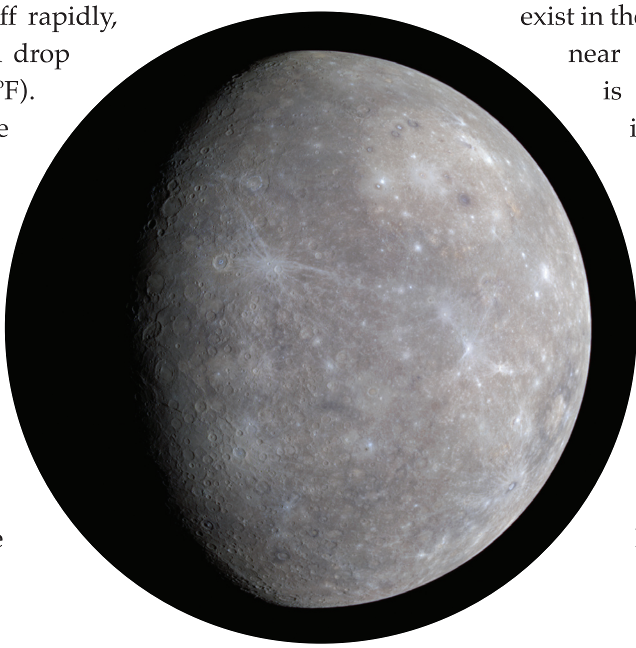


Earth and Mars Orbit Transparency #3



Mission Log: Mercury

Mercury is the closest planet to the Sun. Its diameter is only a little more than a third of the Earth. It has a very thin atmosphere, which is only a little more substantial than a vacuum. Sunlight heats up the surface of the planet to high temperatures during the day, up to 450ºC (840ºF). At night, the surface cools off rapidly, and the temperatures can drop down to -180ºC (-300ºF). This daily temperature variation is the largest of all of the planets. However, Mercury's day is much longer than Earth's. Due to Mercury's closeness to the Sun and its slow rotation, the length of one day on Mercury is equal to 176 Earth days; that is, the time from one sunrise to another on the surface of Mercury is 176 Earth days. Mercury orbits the Sun once every 88 Earth days; that is, its year is 88 Earth days long. This means that one day on Mercury is two of its years long. There is no liquid water on Mercury, although it is possible that water ice could exist in the permanently shaded craters near Mercury's poles. Mercury is a planet with a very large iron core and a thin mantle compared with the Earth. Mercury is bombarded by intense solar radiation since its atmosphere is not sufficiently thick to provide much protection (unlike the atmosphere of Earth), and it is so close to the Sun. It is unlikely that any life forms could live on Mercury.



Spacecraft Missions to Mercury:

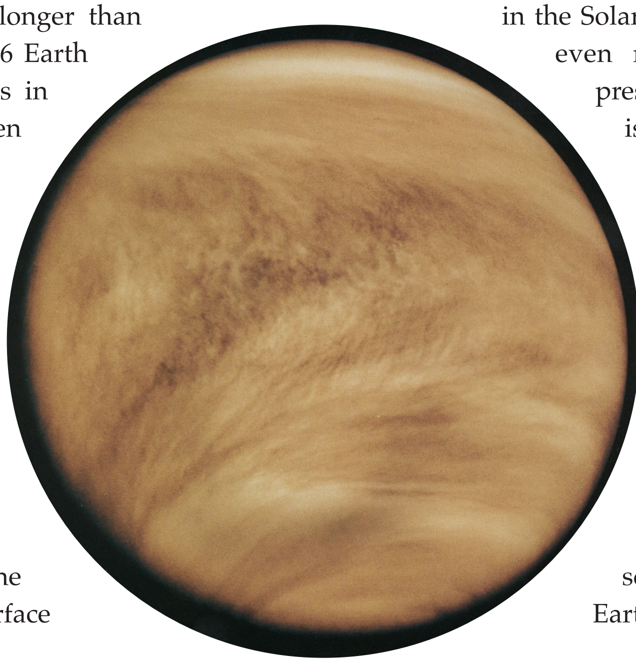
- Mariner 10 (1974-1975): The spacecraft flew by the planet three times, mapped 45% of the surface and revealed that Mercury had greater mass than previously thought.
- MESSENGER (launched in 2004): This orbiter mission flies by Mercury three times in 2008 and 2009 before going into orbit around the planet in 2011. During its one-year orbital mission, the spacecraft will map the entire surface and conduct a comprehensive study of the planet and its space environment.

For a complete list of past, current, and future missions to Mercury, see http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html

(Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; http://solarsystem.nasa.gov/multimedia/gallery/messenger_new_big.jpg)

Mission Log: Venus

Venus is the second planet from the Sun. It is a near twin in size to the Earth but is otherwise very different. Venus's rotation is somewhat unusual in that it is both very slow (243 Earth days per one Venus day, slightly longer than Venus's year, which is 226 Earth days long), and it rotates in a clockwise direction when viewed from above the north pole of the Sun (this is opposite to the rotation of the Earth and most other planets.) Venus has a very thick carbon dioxide atmosphere that traps heat from the Sun during the day and does not let the surface cool at night. As a result, the temperatures on the surface of Venus are over 464ºC (867ºF). Similar greenhouse effect operates also on the Earth, but on Venus the process went to extremes and raised the temperature to the hottest surface temperature on any planet in the Solar System. To make the planet even more inhospitable, the air pressure on the surface of Venus is about 90 times as high as the air pressure at sea level on Earth. Any water that might have existed on the surface of Venus in the past has long since evaporated, and finding life on the planet is not likely (though not entirely impossible.) We may learn a lot about Earth by learning why Venus, in so many ways similar to the Earth, turned out so differently.



Some of the Most Successful Spacecraft Missions to Venus:

- Mariner 2 (1962): This fly-by mission confirmed that Venus is a very hot planet with a cloud-covered atmosphere composed primarily of carbon dioxide.
- Venera 7 (1972): This lander was the first human-made probe to send back data from the surface of another planet.
- Venera 9 (1975): The mission featured an orbiter, as well as a lander, which sent back the first images of the surface of Venus.
- Pioneer Venus (1978-1992): The mission included an orbiter, which used radar to make the first high-quality map of the surface of Venus, and atmosphere probes, which descended into the atmosphere to analyze it in greater detail.
- Magellan (1990-1994): This orbiting mission mapped 98% of the surface of Venus. Most of what we know of the surface features of Venus is due to this spacecraft.
- Venus Express (Arrived in 2006): Studying the properties of the atmosphere to understand its greenhouse effect better; also looking for volcanic or seismic activity.

For a complete list of past, current, and future missions to Venus, see http://nssdc.gsfc.nasa.gov/planetary/planets/venuspage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Venus_Clouds.jpg)

Mission Log: The Moon

The Moon is Earth's celestial neighbor. It is about 384,000 km (239,000 miles) from the Earth, and its diameter is about one quarter of Earth's. It takes the Moon 27 1/3 days to go once around the Earth. The Moon's composition is very similar to those of Earth and the other rocky, Earth-like planets in the Solar System. In fact, its similar composition to the Earth's crust material was a crucial clue in developing an understanding of its origin. The Moon is thought to have formed when a Mars-sized object smashed into the forming Earth billions of years ago. Material was blasted into orbit around Earth by this collision and later collected together to become the Moon. The surface of the Moon is heavily cratered as a result of meteoroid bombardment in the past. There are two main types of terrain on the Moon: the old, light-colored, heavily cratered highlands, and the younger, dark, smooth areas called maria. About 382 kg (842 lbs) of rock samples from the surface of the Moon have been returned for laboratory studies, which have revealed lots of information about the composition, the structure, and the history of the Moon. There are currently plans to send humans back to the Moon and even establish a permanent colony there.

Some of the Most Successful Spacecraft Missions to the Moon:

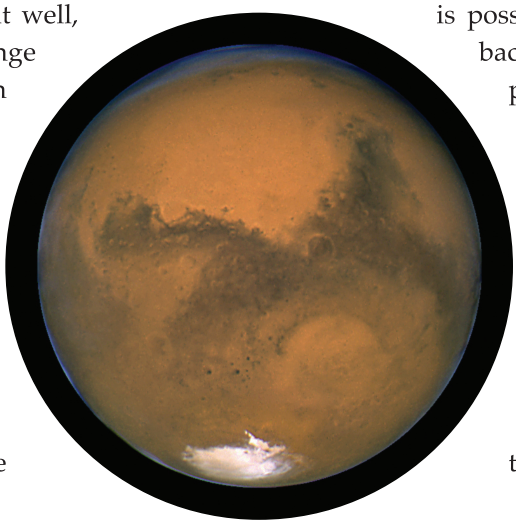
- Luna 1 (1959): This fly-by mission was the first spacecraft to reach the Moon.
- Luna 2 (1959): This lander mission was the first spacecraft to reach the surface of another world: it crashed on the surface (as planned) and provided data on the conditions near the surface
- Luna 3 (1959): This fly-by mission took the first pictures of the far side of the Moon.
- Luna 9 (1966): This lander mission was the first to make a soft landing on another world and return data from the surface.
- Lunar Orbiter 1-5 (1966-1967): These orbiter missions mapped the surface of the Moon and looked for landing sites for future missions.
- Apollo 11,12,14,15,16,17 (1969-1972): These orbiter/lander missions were the first to take humans to the surface of another world. The astronauts made close-up observations of the surface and returned samples back to the Earth for analysis.
- Clementine (1994): This orbiter mission mapped the surface of the Moon at high resolution. It also discovered there might be water ice under the surface near the south pole of the Moon.
- Lunar Prospector (1998-1999): This orbiter mission mapped the surface and suggested there may be water ice under the surface near the north pole of the Moon.

For a complete list of past, current, and future missions to the Moon, see http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/PIA00405.jpg)

Mission Log: Mars

Mars is the fourth planet from the Sun. It is about half the size of Earth in diameter. The Martian day is about 43 minutes longer than the Earth day, and its year is 686 Earth days. Mars has a carbon dioxide atmosphere, but it is extremely thin, only about 1/100 as thick as Earth's atmosphere. The thin air does not retain heat well, and surface temperatures range from a frigid -130ºC (-200ºF) on a winter night to 27ºC (80ºF) at the equator on a summer day. Mars appears red because iron contained in the rocks and sand on its surface has combined with oxygen in the atmosphere through the same process that produces rust on Earth. Mars occasionally has dust storms that cover the whole planet for months. Mars has polar ice caps made of carbon dioxide ice ("dry ice") and water ice. The size of the polar ice caps changes significantly during the planet's seasons. While Mars is very dry today, it used to have lots of liquid water in the form of rivers and seas on its surface in the past. It is possible that living beings (such as bacteria) could have existed on the planet then. Or, perhaps there are simple life forms still on Mars similar to bacteria on Earth that can survive in frigid conditions by creating anti-freeze chemicals that keep the water in their cells from freezing. In any case, Mars looks like the likeliest place for life to exist outside of the Earth.



Some of the Most Successful Spacecraft Missions to Mars:

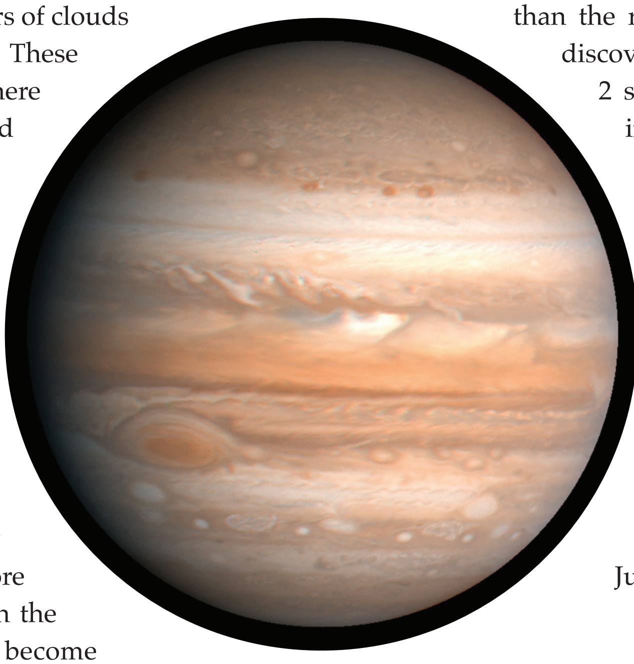
- Mariner 4 (1965): This fly-by mission took the first close-up images of the surface of Mars.
- Mariner 9 (1971-1972): This orbiter mission provided detailed views of the huge volcanoes on the Martian surface, the giant canyon systems, the polar ice caps and Mars's two moons, Phobos and Deimos.
- Viking 1 and 2 (1976-1982): These combined orbiter/lander missions sent back the first images from the surface, made life-detection experiments (with inconclusive results), recorded a marsquake, and monitored weather.
- Mars Pathfinder (1997): Included a stationary lander and the first surface rover that successfully operated on another planet.
- 2001 Mars Odyssey (2001-2006): This orbiter found evidence for large amounts of water ice under the surface near the south pole of Mars.
- Mars Exploration Rovers (Arrived in 2004): These roving landers confirmed that Mars had a lot of water on its surface in the past.
- Mars Express (Arrived in 2003): This orbiter mission has gathered detailed information on the surface features and minerals, as well as the atmosphere.
- Phoenix Mas (Arrived in 2008): The lander mission examines the climate and weather near the north pole of Mars; also digs underground to look for water ice.

For a complete list of past, current, and future missions to Mars, see http://nssdc.gsfc.nasa.gov/planetary/planets/marspage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Hubble_Mars.jpg)

Mission Log: Jupiter

Jupiter is the fifth planet from the Sun and the largest planet in the Solar System. It is about 318 times as massive as Earth, and over 1,300 Earths could fit inside of it. Jupiter is a gas giant mostly made of hydrogen and helium. Jupiter has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its massive atmosphere. These upper layers of the atmosphere show complicated wind patterns. The winds blow in opposite directions in the light-colored zones and dark belts. Perhaps the most recognizable feature on Jupiter's visible surface is the Great Red Spot, a huge storm, more than twice the diameter of Earth, which has been seen by observers on Earth for more than 300 years. Deeper in the atmosphere, the gases become thicker until they eventually turn into a liquid. At its center, Jupiter may have a solid, rocky core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Jupiter has at least 63 moons and a faint ring system. The ring system is much fainter than the rings of Saturn and was not discovered until the Voyager 1 and 2 spacecraft flew by the planet in 1979. One day on Jupiter is about 10 hours long, and its year is about 12 Earth years. Jupiter radiates more energy into space than it receives from the Sun. This excess energy, produced by the planet being compressed under its own gravity, is thought to be ultimately responsible for the complex motions in Jupiter's atmosphere.



Some of the Most Successful Spacecraft Missions to Jupiter:

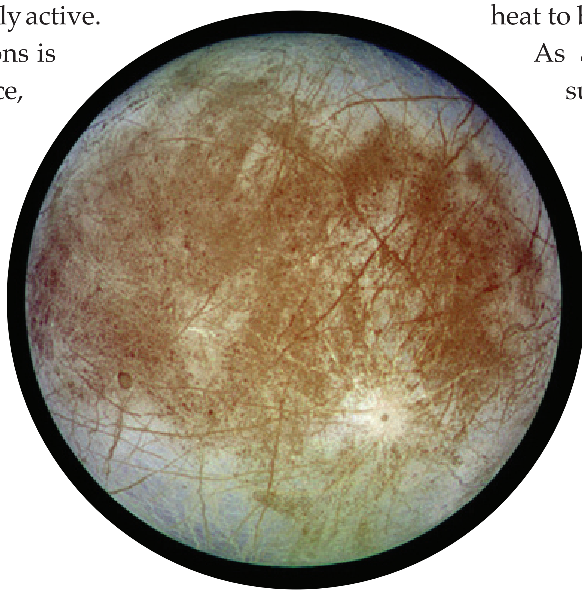
- Pioneer 10 (1973): This fly-by mission provided the first close-up images of Jupiter.
- Pioneer 11 (1974): This fly-by mission provided dramatic images of the Great Red Spot and made the first observations of the planet's polar regions.
- Voyager 1 and 2 (1979): These fly-by missions discovered that Jupiter has complicated atmospheric phenomena, as well as lightning and aurora. They discovered that Jupiter has rings and that Io, one of Jupiter's moons, has active volcanoes. They also mapped part of the surface of Europa, another of Jupiter's moons.
- Galileo (1995-2003): The orbiter portion of the mission was the first to orbit Jupiter, and the atmosphere probe that plunged into the planet's atmosphere provided the first measurements of the properties of a giant planet underneath the surface clouds.

For a complete list of past, current, and future missions to Jupiter, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

(Picture credit: NASA; http://nssdc.gsfc.nasa.gov/imgcat/hires/vg2_usgs_1990.jpg)

Mission Log: Europa

Europa is one of the 63 known moons of Jupiter. Its surface is very smooth: few features more than a few hundred meters high have been seen. There are few craters on Europa, which suggests that the surface is young and geologically active. One of the possible explanations is that the moon has an icy surface, and the ice has covered older craters. The pictures taken by the Galileo spacecraft, which studied the Jupiter system from 1995 to 2003, confirmed that Europa is covered by water ice that is probably a few kilometers/miles thick. Because of the way Europa orbits Jupiter, the planet's gravitational forces tug at the moon a little bit differently at various parts inside it, and at different points on its orbit, causing heat to be generated inside the moon. As a result, underneath the icy surface, there could be a liquid water ocean. Since liquid water is thought to be one of the requirements for living beings, could life exist on Europa? This question remains currently unanswered.



Spacecraft Missions to Europa (Jupiter system):

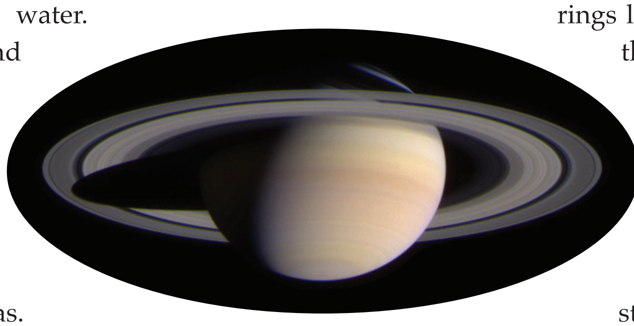
- Voyager 1 & 2 (1979): These fly-by missions mapped a fraction of the surface of Europa as they passed through the Jupiter system.
- Galileo (1995-2003): This mission, while orbiting Jupiter, flew by the planet's moons, including Europa, several times. The data shows that underneath the icy surface, the moon has a liquid water ocean.

For a complete list of past, current, and future missions to the Jupiter system, including Europa, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

(Picture credit: NASA; http://nssdc.gsfc.nasa.gov/imgcat/hires/gal_p48040.jpg)

Mission Log: Saturn

Saturn is the sixth planet from the Sun and the second largest planet in the Solar System after Jupiter. Its diameter is about 85% of Jupiter's but it is a lot lighter: its mass is about a third of Jupiter's. This means that it has a very low density. In fact, its density is the lowest of all the planets and less than the density of water. Still, in composition and internal structure, the planet is thought to be fairly similar to its larger sibling. Like Jupiter, Saturn is a gas giant mostly made of hydrogen and helium gas. Saturn has no solid surface we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light-colored zones and dark belts, where the winds blow in opposite directions, but the bands are not as prominent as on Jupiter. Deeper in the atmosphere, the gases get thicker, until finally they turn into a liquid. At its center Saturn has a solid, rocky core a few times the size of Earth. Saturn's day is about 10.5 hours long, and its year is about 29.5 Earth years. Saturn has at least 60 moons, and perhaps many more that are yet to be discovered. Saturn's most striking property may be its exquisite ring system. The rings are surprisingly thin: even though they are 250,000 km (155,000 miles) in diameter, they are less than one kilometer (0.6 miles) thick. Even though the rings look solid when viewed from the Earth, they are actually composed of millions of small icy particles varying in size from a centimeter (less than an inch) up to a kilometer (half a mile). Scientists are still trying to determine the origin of the ring particles; the most commonly accepted suggestions are that they are bits of dust blown off the planets' moons by asteroid or meteoroid impacts, or leftovers from the breakup of larger moons. Saturn radiates more energy into space than it receives from the Sun. Some of the excess energy comes from the planet being compressed under its own gravity, but some may come from other sources, such as helium gas condensing in Saturn's atmosphere into droplets and raining down deeper into the planet.



Spacecraft Missions to Saturn:

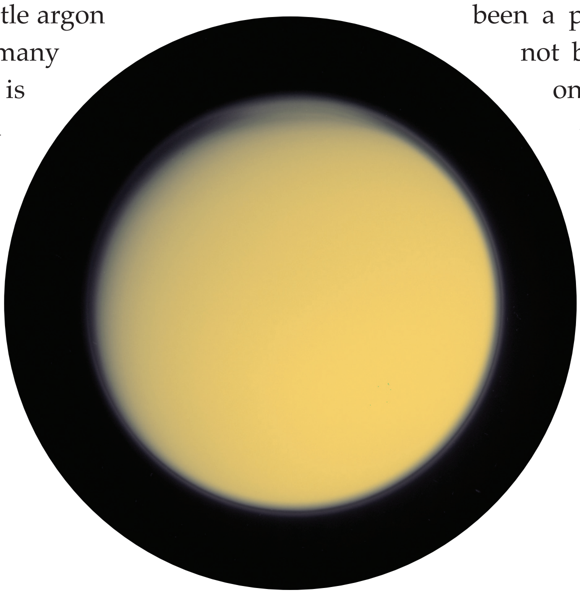
- Pioneer 11 (1979): This fly-by mission provided the first close-up images of Saturn.
- Voyager 1 and 2 (1980-1981): These fly-by missions provided detailed information on the planet, its atmosphere, moons and rings. For example, they discovered shepherd moons that keep the rings stable.
- Cassini-Huygens (Arrived in 2004): This orbiter mission was the first to explore the Saturn system from orbit. The mission has provided detailed information on the planet's clouds and magnetic field, as well as made close-up studies of the moons and the rings.

For a complete list of past, current, and future missions to Saturn, see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

(Picture credit: NASA/JPL/Space Science Institute; http://solarsystem.nasa.gov/multimedia/gallery/Saturn_Approach.jpg)

Mission Log: Titan

Titan is one of the 60 known moons of Saturn. Titan's most interesting feature is that it is the only moon in to Solar System to have a significant atmosphere. At Titan's surface, the atmospheric pressure is 1.5 times that of Earth's at sea level. The atmosphere is composed primarily of molecular nitrogen with a little argon and methane mixed in. In many ways, Titan's atmosphere is similar to the conditions on Earth early in its history when life first emerged on our planet. But it is this thick hazy atmosphere that makes it so hard to see Titan's surface. The images taken by spacecraft exploring the moon close-up have revealed an active surface with flowing liquids (composed of methane, rather than water) and many meteorological and geologic processes in action. Titan could have been a possible host for life, if it had not been so cold—the temperature on the surface of Titan is frigid -180ºC (-290ºF)—that no living beings that we know of could survive on its surface.



Spacecraft Missions to Titan:

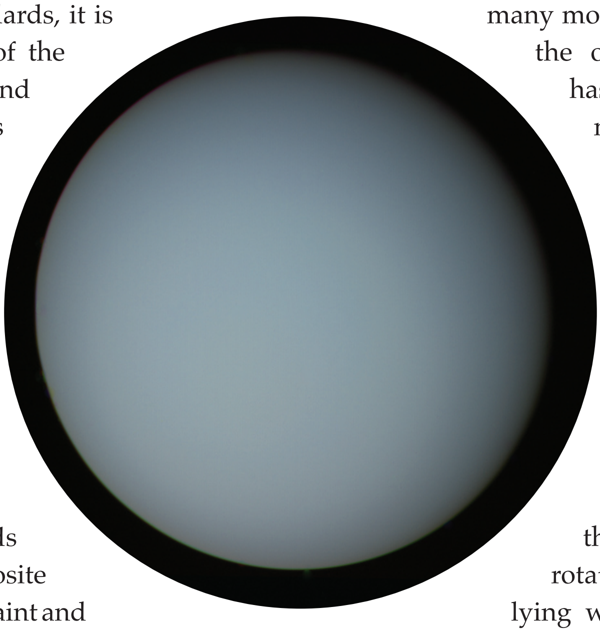
- Pioneer 11 (1979): This fly-by mission provided the first close-up images of Titan as it passed through the Saturn system.
- Voyager 1 and 2 (1980-1981): These fly-by missions provided more information on Titan's hazy atmosphere but were not able to see the surface.
- Cassini-Huygens (Arrived in 2004): The main spacecraft, Cassini, orbits Saturn and has flown by Titan several times, providing information on the moon's atmosphere and surface features. In 2005, the Huygens probe descended through Titan's thick atmosphere and landed on the surface. The probe send back images from the surface and provided other detailed data for about 90 minutes.

For a complete list of past, current, and future missions to the Saturn system (including Titan), see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

(Picture credit: NASA/JPL/Space Science Institute; http://photojournal.jpl.nasa.gov/tiff/PIA06122.tif)

Mission Log: Uranus

Uranus is the seventh planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Neptune in size. Uranus's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of rock and ice, and even though it has an extensive atmosphere by Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Uranus (as well as Neptune) is sometimes called an "ice giant" instead of a gas giant. Uranus has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light and dark bands where the winds blow in opposite directions, but they are very faint and not visible in images taken of the planet without extensive image enhancements. However, it may be that the visibility of the bands changes according to the planet's seasons. Underneath Uranus's atmosphere, the mixture of ice and rock is probably distributed uniformly, and the planet may not have a solid core at all. Uranus's day is about 17 hours long, and its year is about 84 Earth years. It rotates in a clockwise direction when viewed from above the north pole of the Sun; this is opposite to the rotation of Earth and most other planets. Uranus has at least 27 moons (and perhaps many more yet to be discovered.) Like the other giant planets, Uranus has a ring system, though it is much fainter than the rings of Saturn. Uranus's unique feature is that it appears to have been knocked over sometime in the past. Most planets orbit around the Sun spinning upright; that is, their rotational axes are almost perpendicular with respect to their orbit (with small deviations, like the Earth's 23.5º tilt). Uranus's rotation axis, however, is almost lying within its orbital plane. The cause of this unique feature is not certain, but it may have been caused by an impact of a large object, such as a large asteroid or moon. Unlike the other giant planets in the Solar System, Uranus does not appear to have an internal heat source. Why this is the case is not certain.



Spacecraft Missions to Uranus:

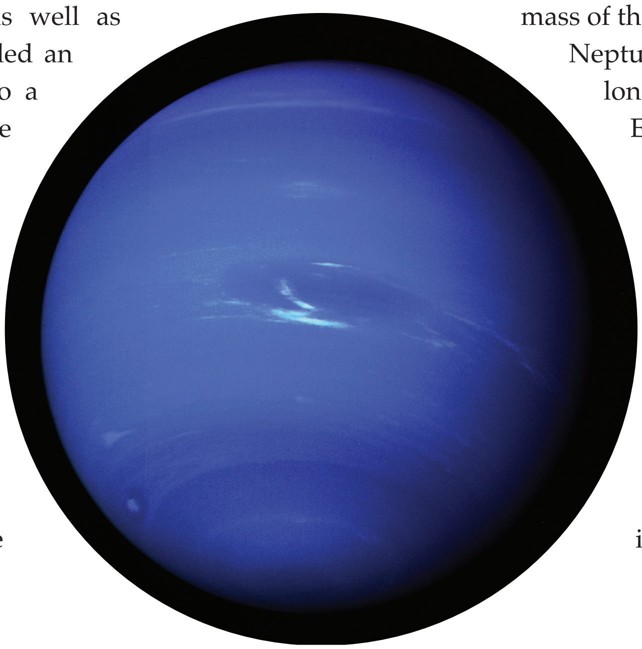
- Voyager 2 (1986): This fly-by mission provided the first close-up images of Uranus. Its observations have produced much of our current knowledge of the planet, its rings and moons. It also found out that the magnetic field is peculiar in its properties (origin, orientation, etc.)

For a complete list of past, current, and future missions to Uranus, see http://nssdc.gsfc.nasa.gov/planetary/planets/uranuspage.html

(Picture credit: NASA and Heidi Hammel / Massachusetts Institute of Technology; http://photojournal.jpl.nasa.gov/tiff/PIA00032.tif)

Mission Log: Neptune

Neptune is the eighth planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Uranus in size. Neptune's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of rock and ice, and even though it has an extensive atmosphere by Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Neptune (as well as Uranus) is sometimes called an "ice giant" as opposed to a gas giant. We cannot see Neptune's solid surface, and the apparent visible surface is just the top layers of clouds in its atmosphere. Giant storm centers can be seen on its visible surface, similar to those on the other giant planets. Also, like on the other giant planets, the atmosphere has great wind patterns creating bands on the atmosphere where winds blow in different directions. In fact, the winds on Neptune are the fastest in the Solar System, reaching speeds of 2,000 km/hour (or 1,200 miles/hour). Underneath the atmosphere, the mixture of ice and rock making up the bulk of the planet is probably uniformly mixed, though there may be a solid core about the mass of the Earth at the planet's center. Neptune's day is about 17 hours long, and its year is about 165 Earth years. It has at least 13 moons; probably many more are yet to be discovered. Like the other giant planets, Neptune has a ring system, though it is much fainter than the rings of Saturn. Neptune radiates more energy into space than it receives from the Sun. The source of this internal energy is uncertain.



Spacecraft Missions to Neptune:

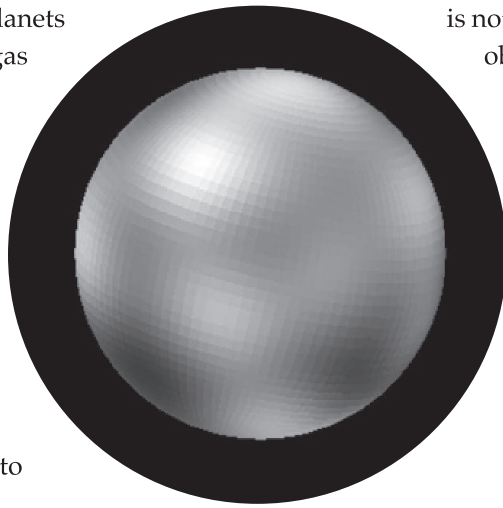
- Voyager 2 (1986): This fly-by mission provided the first close-up images of Neptune. Its observations have produced much of our current knowledge of the planet, its rings and moons. It detected auroras on Neptune, and showed the atmosphere to be very active with high winds and large storms.

For a complete list of past, current, and future missions to Neptune, see http://nssdc.gsfc.nasa.gov/planetary/planets/neptunepage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Neptune_Full.jpg)

Mission Log: Pluto

Pluto used to be known as the ninth planet, but it always seemed a bit odd when compared with the other eight planets. Like the terrestrial planets (Mercury, Venus, Earth, and Mars), it is small, but, because it is a mixture of rock and ice, its density is low, and it is not located in the same part of the Solar System as the terrestrial planets. Instead, it is located in the outer part of the planetary realm of the Solar System, where the giant planets reside, but it certainly is not a gas or an ice giant, either. Instead, Pluto appears to be more closely related to the hundreds of objects astronomers have discovered beyond Neptune's orbit in recent years. When one of these so-called Kuiper Belt Objects was discovered to be larger than Pluto, the International Astronomical Union decided in 2006 that Pluto cannot be considered a real planet any more, and instead belongs to a new class of objects called dwarf planets. As a result, there are now only eight planets in the Solar System, and Pluto is just an example of the new group of objects called dwarf planets. There are probably many more dwarf planets in the outer regions of the Solar System yet to be discovered. Pluto has three moons, but this is not unusual for smaller Solar System objects: many dwarf planets, Kuiper Belt Objects, and asteroids have moons. Pluto's day is about 6.4 Earth days long, and its year is about 248 Earth years. The frigidly cold temperatures—the temperature on the surface of Pluto is thought to reach -230ºC (-450ºF)—make it unlikely for any living beings to live on the dwarf planet.



Spacecraft Missions to Pluto:

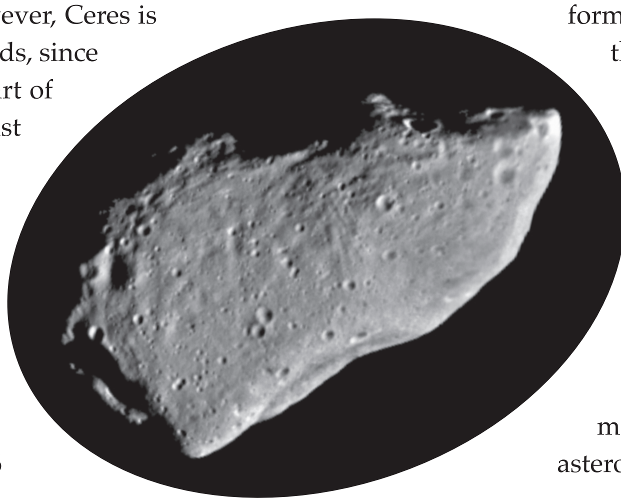
- New Horizons (will arrive in 2015): This fly-by will be the first mission to provide close-up observations of Pluto and its moons.

For a complete list of past, current, and future missions to Pluto, see http://nssdc.gsfc.nasa.gov/planetary/planets/plutopage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/nssdc_hst_pr96_09a.jpg)

Mission Log: Asteroids

Asteroids are small rocky objects that can be found in different regions of the Solar System. They orbit the Sun like planets, but they are a lot smaller. Ceres used to be known as the largest asteroid; it is about 950 km (590 miles) in diameter. However, Ceres is now classified as a “dwarf planet”, a new category of objects in the Solar System defined by the International Astronomical Union in 2006 to include objects like Ceres and Pluto, which are too small to be considered real planets, but resemble them in many other ways. However, Ceres is still associated with asteroids, since it is located in the same part of the Solar System as the vast majority of asteroids—the Asteroid Belt, a region between the orbits of Mars and Jupiter. The largest asteroids are Pallas, Vesta and Hygiea, which are between 400 km (249 miles) and 525 km (326 miles) in diameter. There are hundreds of thousands of known asteroids. Astronomers probably have seen almost all of the asteroids larger than 100 km, and about half of those with diameters in the 10-100 km range. But there are probably millions of asteroids with sizes in the 1 km range that have never been seen. Some of the moons of planets, such as the two moons of Mars and the outer moons of Jupiter and Saturn, are similar to asteroids, and they may be captured asteroids rather than having formed in the same way around the planet as other moons. Asteroids are thought to be remnants of the formation of the Solar System that did not become planets. The minerals on the rocky asteroids could be useful resources for space explorers, so sometime in the distant future humans might establish mining on asteroids.



Some of the Most Successful Spacecraft Missions to asteroids:

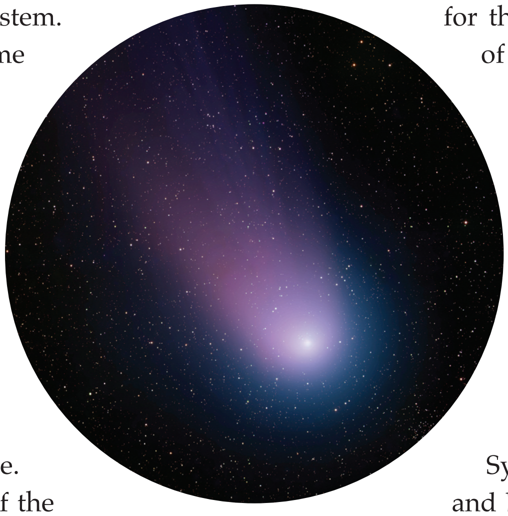
- Galileo (1991, 1993): On its way to Jupiter, the spacecraft flew by the asteroids Gaspra and Ida, providing the first close-up images of asteroids, and also discovering the first moon (Dactyl) of an asteroid (Ida).
- NEAR Shoemaker (2000-2001): This orbiter provided a lot of information on the asteroid Eros before landing on the asteroid, in so doing becoming the first spacecraft to make a soft landing on a small Solar System body.

For a complete list of past, current, and future missions to asteroids, see http://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html

(Pictured above: Asteroid Gaspra; picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00118.tif)

Mission Log: Comets

Comets reside in the outer regions of the Solar System. They are dirty ice balls composed of ices (water ice, as well as other kinds of ices, such as carbon dioxide, ammonia, and methane ices), rock, and dust. They are thought to be remnants of or the actual building blocks of (at least the outer) planets, and, therefore, are a subject of great interest for researchers interested in understanding the early history of the Solar System. Comets spend most of their time in the outer reaches of the Solar System and are not visible to observers on Earth. There, the comet consists of only its solid body, the nucleus, which is only a few kilometers/miles across and darker than charcoal. It is only when a comet's orbit takes it to the inner parts of the Solar System that a comet becomes observable. The Sun heats the frozen body of the comet, and causes ices on the comet's surface to sublimate—change directly from solid to gas. The gases blown off the nucleus, as well as specks of dust caught in the outflow, form a large cloud of gas and dust particles around the nucleus, called the coma, which can be over 1.6 million km (1 million miles) in size. Sunlight pushes against the dust particles in the coma, while the solar wind—fast outflow of electrically charged particles from the Sun—interacts with the gas. As a result, gas in the coma is pushed away from the nucleus, forming a very long tail stretching away from the comet pointed away from Sun. It is not unusual for the tails of comets to extend tens of millions of kilometers/miles. The dust that is forced off the coma forms a second tail that is curved away from the comet's direction of motion. If comets venture close to Earth, they can be some of the most striking objects in the sky. Because comets are small, because they are located in the far reaches of the Solar System during much of their orbit and because they have very unstable surfaces when they get close to the Sun, they are unlikely to host living beings. However, they might be sources of raw materials for space explorers, so sometime in the distant future humans might venture out and establish mining on comets.



Some of the Most Successful Spacecraft Missions to comets:

- International Cometary Explorer (1985): This fly-by mission was the first to obserbe a comet close-up.
- Stardust (2004): This fly-by mission collected samples from the coma of comet Wild 2 and returned them to Earth for analysis.
- Deep Impact (2005): The fly-by spacecraft included a lander/impactor that smashed into comet Tempel 1.

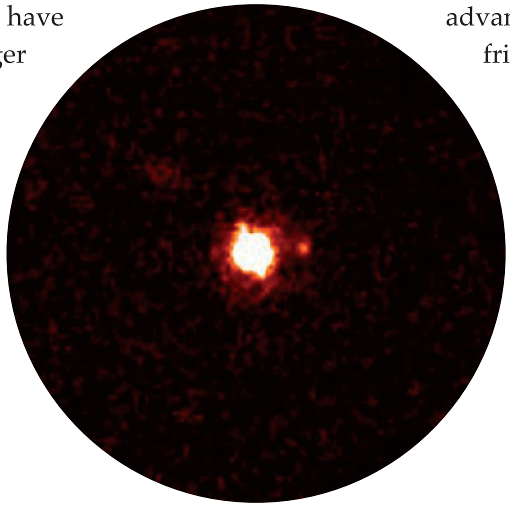
For a complete list of past, current, and future missions to comets, see http://nssdc.gsfc.nasa.gov/planetary/planets/cometpage.html

(Pictured above: Comet C/2001 Q4 – NEAT; picture credit: T. Rector (University of Alaska Anchorage), Z. Levay and L. Frattare (Space Telescope Science Institute) and National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation; http://solarsystem.nasa.gov/multimedia/gallery/Comet_NEAT.jpg)

MESSENGER
Mission to Mercury

Mission Log: Kuiper Belt Objects

Since 1992, astronomers have found hundreds of objects similar to Pluto beyond Neptune's orbit. These objects are all small icy worlds most commonly called Kuiper Belt Objects, after the astronomer Gerard Kuiper, though they are sometimes also called trans-Neptunian objects, because they reside in space beyond the orbit of Neptune. The Kuiper Belt region, located at a distance of 30 to 50 times as far from the Sun as the Earth, may have 35,000 objects with diameters larger than 100 km (60 miles). These objects are similar to Pluto: they are small bodies made of a mixture of rock and ice. Most of the Kuiper Belt Objects discovered to date are smaller than Pluto, but detailed observations of an object named Eris, first discovered in 2003, revealed that it is larger than Pluto. This led the International Astronomical Union to decide in 2006 that Pluto (as well as Eris) belongs to a new class of objects called dwarf planets. There probably are more dwarf planets, in addition to smaller KBOs, yet to be discovered in the Kuiper Belt. Because the objects there are so far away from the Sun and are so small, they are hard to discover without powerful telescopes and advanced observation techniques. The frigidly cold temperatures in the Kuiper Belt—the temperatures on the surfaces of KBOs are not thought to reach much above -230°C (-450°F)—make it unlikely for any living beings to live there, and these harsh conditions certainly make the objects very inhospitable destinations for human explorers.



Spacecraft Missions to Kuiper Belt Objects:

- New Horizons: After flying by Pluto in 2015, the spacecraft probably will be directed to fly by one or more Kuiper Belt Objects, providing the first close-up observations of these objects.

(Pictured above: Dwarf planet Eris; picture credit: Courtesy W. M. Keck Observatory; https://www.keckobservatory.org/images/gallery_pictures/4_73.jpg)

STRANGE NEW PLANET

Your name: ______________________________

Other members of your team: ______________________________

____

____

The name of your team: ______________________________

Date: ____________

Introduction

In this activity, your team will make a model planet for your partner team to explore. You will then explore the model planet created by your partner team through different methods of exploration.

A. Create a Model Planet

Use a plastic ball, a Styrofoam© ball, or round fruit as your model planet. Use materials available to your class to decorate the planet with features modeling landforms, moons, atmosphere, etc. For example, you can:

- Carve channels with a toothpick or a knife;
- Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms);
- Apply scents (vinegar, perfume, etc.) sparingly to a small area;
- Use a sheet of colored cellophane to wrap up the model planet (to represent atmosphere);
- Create clouds by using cotton and glue;
- Attach a toothpick with a piece of modeling clay at the end (to represent a moon).

Record each feature in the table on the next page. Use your imagination to create a unique planet! Make sure to place some features discreetly so that they are not obvious when seen from a distance. Write down on an index card the name of your team and the name of your planet to identify it when all planets are gathered together.

The name of your planet: ________________________________

Record in the table below each feature you place on the model planet
(example: 1 – toothpick with clay – moon)

Feature Number	Item Used	Feature Modeled

B. Mission 1: Earth-Based Observations

1) Estimate your distance from your target world (meters or feet):

2) A paper towel tube or a rolled-up sheet of paper will act as your Viewer with which you will make your observations. If your teacher wants you to simulate the effect of Earth's atmosphere, crumple up and then straighten out a piece of clear cellophane. Attach the piece to the end of your Viewer. If you don't use the cellophane, your observations would be similar to using a space telescope located near the Earth. What types of things do you observe? Use your Viewer to observe the world. Record your observations (color, size, etc.):

3) Discuss your observations with the rest of your team. Record any team observations that differ from yours:

4) As a team, write questions to be explored in future missions to the world. What else do you wish to know and how could you find out that information?

a.

b.

c.

d.

C. Mission 2: Fly-by

Each person on your team will have a turn at walking quickly past the model planet and observe it using your Viewers (without the piece of cellophane.) Make sure you keep farther than the distance of five feet from the planet. Answer the questions below when you have returned from your fly-by.

1) Record your observations of the planet. What did you see that was the same as your Earth-based observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that differ from yours:

4) As a team, write observations you would like to make on an orbiting mission:

a.

b.

c.

d.

D. Mission 3: Orbiter

Each team member gets two minutes to orbit (circle) the planet and observe it using the Viewers (without the piece of cellophane.) Make sure you keep farther than the distance of two feet from the planet. You must circle the planet the whole time; do not stop to look more carefully at any part of the planet. After your observation, return to Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based or fly-by observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

____

____

____

____

____

2) Discuss your observations with the rest of your team. Record any team observations that differ from yours:

____

____

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____

____

3) As a team, develop a plan for a lander expedition onto the planet's surface.

a. Where will you go and why? How did your team decide where to land?

____

____

____

b. What are the risks and benefits of landing there?

____

____

____

c. What specifically do you want to explore at this site?

d. What type of special equipment or instruments would you need to accomplish your exploration goals? (Remember, anything you bring has to be small and light enough to fit aboard a spacecraft.)

E. Mission 4: Lander

If your partner team used colored cellophane on their model planet to represent atmosphere, remove it carefully. Mark your landing site on your target planet with a push-pin or a small piece of masking tape. Place the Viewer around the push-pin, and draw a circle on the model planet's surface around the Viewer. Set the Viewer aside. The circle marks the maximum area around the landing site, which you can explore. Do not make any observations of features beyond the circle. You have a total of five minutes to explore the landing site. After your observation, return to Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based, fly-by, or orbital observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that differ from yours:

3) Was your mission successful? Why or why not?

4) Now that you have landed once on the planet, are the additional questions you would like to answer during follow-up missions?

5) What were the greatest challenges of this mission (personally and as a team)? What would you change for the next mission?

F. Compare Different Mission Types

Write down the pros and cons of the different mission types. For example, what kind of science can you do? What may be the difficulties or the hazards? Think of both your experiments in this activity and what scientists in real life could experience with the different mission types.

1) Earth-Based Observations:

Pros:

Cons:

2) Fly-by Mission:

Pros:

Cons:

3) Orbiter Mission

Pros:

Cons:

4) Lander Mission

Pros:

Cons:

Mission Design

Your team: ______________________________

____

____

____

Date: __________

Introduction

Your team will design a spacecraft mission to explore another world in the Solar System. You must decide which world you want to explore, what you want to learn about your target world, and how you want to accomplish your mission. It can be tricky because space exploration is expensive and hazardous. Along the way, you may need to re-examine your mission goals based on available funding and other constraints. At the end, you must prepare a comprehensive proposal that you could submit to NASA. In your proposal, you must make a convincing argument why your mission should be selected for funding. Good luck!

1. Choose a World to Explore

Within your team, choose a world you would like to explore. You can use the Mission Log to find an interesting world to examine. If you are operating with a limited budget, you may also want to look at Table S1 in the Mission Cost List to help decide which world to investigate, since some worlds are more expensive to explore than others.

Your target world: ______________________________

A) The basic cost to explore this world (table S1, Mission Cost List): __________

This includes the approximate cost associated with building the spacecraft, sending it on the journey to explore your target world, communicating with the spacecraft, as well as receiving and analyzing the data.

2. Mission Goals

Examine the Mission Log to see what is known about this world already. Think of three questions which previous missions have not found out, or additional questions which the previous explorations may have raised and which your mission might be able to answer. These are your mission goals:

Mission Goal 1:

____

____

Mission Goal 2:

____

____

Mission Goal 3:

____

____

3. Type of Mission

Now that you understand what your mission needs to accomplish, you can decide what type of mission (fly-by, orbiter or lander) will best help you meet your goals. Remember the pros and cons of each type of mission, and what you can learn through the different methods. You may also want to check the costs in Table S2 in the Mission Cost List, since some types of missions cost more than others. Also, the more complicated the mission you want to perform, the more chances there are for something to go wrong. The possibility of failure can be estimated by using a risk factor: the higher the factor, the riskier the mission.

Your mission will be (circle one): Fly-by Orbiter Lander

Because:

____

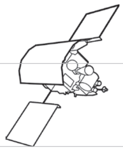
____

____

____

B) Additional cost for this mission (Table S2, Mission Cost List): ____________________

B1) Risk Factor (Table S2, Mission Cost List): ______________________________



MESSENGER

4. Length of Mission

Once you have selected the type of mission, you need to consider the length of the mission. The longer the mission, the greater the cost due to:

- Communications with ground control on Earth to operate the spacecraft and transmit data for analysis;
- Spacecraft operations to make course corrections that may be necessary, to maintain the well-being of the spacecraft, and to respond to any emergencies that may arise;
- Data analysis by scientists on Earth; the more data that is gathered, the more time (or more scientists) are needed for analysis; even after the spacecraft has ceased functioning, there usually is additional time scheduled for data analysis;
- Extra fuel that may be necessary to make course corrections, etc.

The length of the mission depends on the time it takes to travel to the target world, as well as the time spent observing the world. The cost of traveling to the world was considered in cost item A. You must now decide how long your spacecraft will operate once it arrives to your target world. See Table S3 in the Mission Cost List to determine how much the length of your mission affects your plan. A longer mission also means that there are more chances to fail before meeting all mission goals. Mark the appropriate risk factor below, as well.

Time spent to explore the world: ______________________________ years

C) Additional cost for the length of the mission (Table S3, Mission Cost List): ____________

C1) Risk Factor (Table S3, Mission Cost List): ______________________________

5. Payload

Now you have to decide which instruments to include in your spacecraft to help you accomplish your mission goals. See Table S4 in the Mission Cost List for the different kinds of instruments available for your spacecraft. You can pick up to five instruments. Explain why the instrument is necessary to meet your mission goals.

Instrument 1: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 2: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 3: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 4: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 5: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

D) The total cost of your instrument suite (add up the cost of individual instruments:

____

6. Spacecraft Construction

The cost of building the spacecraft depends on how complicated the spacecraft is due to the kind of exploration it will conduct or the environment in which it will operate. Spacecraft and its instruments are often developed together so that each component can fit in their allotted space aboard the spacecraft. As a result, the size of the spacecraft and the size and types instruments must be considered in building a spacecraft. There are also additional costs involved in testing the instruments and the spacecraft. The base price for building your spacecraft has been included in cost item A. However, it is possible to make some savings if you can use similar (or perhaps even spare) components from previous spacecraft. In this case, you don't have to engineer new spacecraft components from scratch. Review the Mission Log to see if a similar mission has been performed in the past to your target or another world. If it has, you can deduct some construction costs.

Is there a similar previous mission (circle one): Yes No

If "Yes":

The name of the similar previous mission: ____________________________________

E) Price reduction for using similar components from previous spacecraft: – $10 million

E1) Using similar components and design from a previous mission reduces the risk, so the risk factor is: 0.5

7. Spacecraft Launch

Launching the spacecraft is a significant cost item, since you have to lift a massive spacecraft from the surface of the Earth to space, and then give the spacecraft a boost toward its target. As a result, the cost of the launch depends on the target world and the mass of the spacecraft, which in turn can depend on many factors, such as the number of instruments, the environment in which the spacecraft has to operate, as well as the type and length of the mission. You can reduce the mass of the spacecraft by building your components smaller; for example, by creating miniature versions of your instruments. The basic cost of launching spacecraft to different worlds on missions of different lengths and types are included in the previous cost items. However, if you have many instruments in your spacecraft, your spacecraft may be heavier than the basic model. You may also want to spend some additional engineering funds to reduce the size of the spacecraft to make the mass of the spacecraft smaller.

Your spacecraft has more than three instruments (circle one): Yes No

If "Yes":

F) Add <u>$50 million</u> for extra launch costs.

You want to spend additional engineering funds to create a smaller version of your spacecraft (circle one): Yes No

If "Yes":

G) Cross out cost item E and risk factor E1), but you gain <u>- $50 million</u> for launch cost savings. Note, however, that miniaturized instruments may not be as reliable, and your risk factor is increased.

G1) Risk factor for miniaturized components: <u>2</u>

8. Total Cost and Risk

Write down the cost items for your mission:

A) ______________________________

B) ______________________________

C) ______________________________

D) ______________________________

E) ______________________________

F) ______________________________

G) ______________________________

Add A)-G) together to calculate the total cost of your robotic spacecraft mission:

____

Write down the risk factors for your mission:

B1) ______________________________

C1) ______________________________

E1) ______________________________

G1) ______________________________

Multiply B1)-G1) with each other to calculate the total risk factor for your robotic spacecraft mission:

____

9. Human Spaceflight versus Robotic Spacecraft Mission

The costs above are calculated for a robotic spacecraft exploring your target world. If you want to have human beings aboard the spacecraft to do the exploration, the costs are much higher. This is because there are significant additional costs associated with keeping the astronauts alive and healthy, such as making sure there is enough food, water, and air for the entire expedition. The astronauts must be protected from the harsh space environment, especially from the vacuum, damaging radiation, and freezing cold or scorching hot temperatures (depending on how far from the Sun the expedition goes.) The mission will also take longer to complete, because you not only need to take the astronauts to your target world and give them time to perform their exploration, but you also must return the crew safely back to Earth. To estimate the additional costs involved with a human spaceflight mission instead of using robotic spacecraft, multiply the total cost from Step 8 by 1,000. Estimating how risky a human spaceflight mission would be compared with robotic spacecraft is difficult, but, for the present purposes, multiply the risk factor from Step 8 by 1,000.

Total cost of a human spaceflight mission: ______________________________

Risk factor for a human spaceflight mission: ____________________________

10. Final Cost

Make final choice between a human spaceflight or robotic spacecraft mission, and write the conclusions here:

Your mission will be done with (mark one):

☐ Robotic spacecraft ☐ Human spaceflight

Final cost of your mission: ____

Final risk factor for your mission: __________________________________

11. Reconsider Mission Details and Mission Goals

Look back at your mission goals or other details and decide if you want to change them. For example, if you think your mission costs too much, you might want to change your mission goals to create a less expensive mission.

Do you want to change the details of your mission? (Circle one)

Yes No

If "Yes," explain how your mission will change. If "No," explain why you want to keep the mission the way it is.

____

____

____

____

12. NASA Proposal

Prepare a proposal of your mission to NASA using the tools provided by your teacher. Be sure your proposal includes:

- Where your spacecraft is going and why;
- The goals of your mission; why are these goals important?
- What type of mission (fly-by, orbiter, lander); why?
- Payload selection and why you chose these instruments;
- Total cost and justification for the costs.

Remember, you are competing with other mission proposals, and not all can be selected for funding. You must be convincing in your argument that your mission offers the best bang for the buck. Good luck!

MISSION COST LIST

Table S1. The basic cost to explore different worlds.

Destination	Cost
Mercury	$200 million
Venus	$100 million
Mars and/or its moons; asteroids and comets in the inner Solar System	$100 million
Jupiter and/or its moons	$300 million
Saturn and/or its moons	$350 million
Uranus and/or its moons	$400 million
Neptune and/or its moons	$450 million
Pluto, other dwarf planets, Kuiper Belt Objects, and comets far from the Sun	$500 million

Table S2. Considerations associated with different types of missions.

Type of Mission	Additional Cost	Risk Factor
Fly-by	(none)	1
Orbiter	$100 million	2
Lander	$200 million	5

Table S3: Considerations associated with missions of different length.

Time Spent Exploring the World (in addition to the time it takes to travel there)	Additional Cost	Risk Factor
1 year	(none)	1
2 years	$1 million	1
5 years	$5 million	2
10 years	$10 million	3

Table S4: Payload cost: the cost and purpose of instruments for various types of missions.

Instrument	Explanation and Purpose	Suitable Missions	Cost
Long-distance camera	Digital camera with a telescope; takes images of the target from a distance	Fly-by Orbiter Lander	$3 million
Stereo Camera	Digital camera that can take 3D images of the target	Fly-by Orbiter Lander	$3 million
Panoramic Camera	Digital camera with a wide field of view; provides panoramic images of target	Lander	$3 million
Microscopic camera	Combination of a microscope and a digital camera; provides detailed images of the target's rocks and soils	Lander	$3 million
Spectrometer 1 (using visible or infrared light)	Measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere)	Fly-by Orbiter Lander	$1 million
Spectrometer 2 (using either visible and infrared *or* visible and ultraviolet light)	Measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere)	Fly-by Orbiter Lander	$3 million
Spectrometer 3 (high-energy and particle radiation)	Measures the properties of magnetic fields, the space environment, and the solar wind in detail	Fly-by Orbiter Lander	$2 million
Magnetometer	Measures basic properties of magnetic fields, the space environment, and the solar wind	Fly-by Orbiter Lander	$0.5 million
Basic Radar	Takes radar images of the target using microwaves bounced off the surface	Fly-by Orbiter	$1 million
Advanced Radar	Measures the properties of the target's atmosphere and features below the surface	Fly-by Orbiter	$2.5 million
Laser Altimeter	Determines the heights of planetary features using a laser beam bounced off the surface of the target	Orbiter	$1.5 million

Instrument	Explanation and Purpose	Suitable Missions	Cost
Seismometer	Monitors quakes on the target world (e.g., marsquakes)	Lander	$0.5 million
Meteorology Instrument Suite	Monitors weather by measuring temperature, pressure, winds, etc.	Lander	$1 million
Geologic Exploration Tool: Rock Abrasion Tool	Powerful grinder that can drill into rocks on the target's surface to provide close-up observations and analysis	Lander	$2 million
Geologic Exploration Tool: Digger Arm	Can dig below the surface to take samples for detailed analysis	Lander	$2 million
Life Experiment Suite	Laboratory experiments designed to look for signs of life (e.g., organic molecules, chemical markers of feeding or respiration)	Lander	$2 million

Answer Key

Student Worksheet 1

B) – E) Answers will vary. The main point of this activity is for students to understand the differences in the kind of information that can be gathered with the four types of missions (Earth-bound, fly-by, orbiter, lander.) The students should also begin to understand the amount of planning that is involved for a mission that leaves the Earth. They should understand that missions become more difficult to plan and conduct as one progresses from a fly-by to an orbiter and a lander mission.

F) Answers will vary. Some possibilities include:

Mission 1: Earth-based observations

Pros:

- Lowest cost (unless the telescope is especially large or space-based, but even in these cases the cost per observation may be lower than for a spacecraft mission, since the telescope can be operated at almost full capacity for a long time.)
- Can easily change instruments that are mounted on the telescope.
- Can easily point the telescope to observe other interesting targets.
- Can collect large amounts of data over long periods of time.
- Can be operated easier than other mission types.

Cons:

- Observations limited: cannot provide as detailed information as spacecraft, especially on small-scale features.
- Observational problems due to the Earth's atmosphere (not applicable for space telescopes.)
- Light pollution: Observational problems due to lights from cities (not applicable for space telescopes.)
- If the target shows only one side to the Earth, only that side can be observed (for example, the Moon.)

- Can only observe the target at night (unless observing the Sun or using radio waves.)
- Cannot observe in bad weather.

Mission 2: Fly-by

Pros:

- Can observe more details of the world than Earth-based observations.
- Can observe the target all the time during approach and departure.
- Can observe the target with several instruments simultaneously.
- Can observe several targets (for example, a planet and its moons; or fly by several planets), if mission is so designed.

Cons:

- Costs more than most Earth-based observations.
- Cannot repair or replace instruments.
- Observation time and area observed is limited by the time the spacecraft is near the target.
- Spacecraft and its instruments must be controlled through computer programs stored onboard the spacecraft for at least part of the time.
- Since data must be stored onboard the spacecraft, and sent to the Earth at a specified time, there are limitations to the amount of data that can be returned.
- Communications become more difficult the farther the spacecraft is from the Earth.

Mission 3: Orbiter

Pros:

- Can observe more details of a target for a longer period of time than a fly-by mission.
- Can observe more of (if not the entire) target
- Can observe global and regional changes on the target's surface and atmosphere over time.
- Can observe the target with several instruments simultaneously.

Cons:

- Cannot repair or replace instruments.
- Costs more than a fly-by mission.
- Needs more fuel than a fly-by mission.
- More hazardous than a fly-by mission.
- Since data must be stored onboard the spacecraft, and sent to the Earth at specific times, there are limitations to the amount of data that can be returned.
- Communications with the Earth may be more difficult if the spacecraft is behind the target during part of its orbit.
- May need to perform orbit corrections maneuvers to remain in orbit around the target.
- Spacecraft and its instruments must be controlled through computer programs stored onboard the spacecraft for at least part of the time.
- Needs more complicated computer programs than a fly-by mission.

Mission 4: Lander

Pros:

- Can observe more details on a small portion of the target than an orbiter mission.
- Can observe changes on the surface of the world or its atmosphere in more detail than an orbiter mission (but only around the landing area.)
- Can observe the area around the landing site with several instruments simultaneously.
- If the lander is movable (e.g., it includes a rover), it can provide detailed observations on several interesting surface features that are within driving distance.
- Can investigate the target's surface, the rocks and the soil in detail, including chemical analysis of samples.
- Can perform experiments to see if there are living beings present.
- Can record seismic events (e.g., marsquakes.)

Cons:

- Cannot repair or replace instruments.
- Needs more fuel than a fly-by mission (but possibly not more than an orbiter mission.)
- Costs more than an orbiter mission.
- More hazardous than an orbiter mission.
- Communications are more difficult because data must be sent from the lander to an orbiting spacecraft and then to Earth.
- Communications with the Earth may be more difficult when the lander is behind the target during the day-night cycle, or when the orbiter that acts as a communications relay is behind the target during part of its orbit.
- Since data must be stored onboard the spacecraft, and sent to the Earth at specific times, there are limitations to the amount of data that can be returned.
- Spacecraft and its instruments must be controlled through computer programs stored onboard the spacecraft for at least part of the time.
- Needs more complicated computer programs than an orbiter mission.

Student Worksheet 2

1. Choose a World to Explore
Answers will vary.

2. Mission Goals
Answers will vary, but listed below are a few examples of issues that remain unknown or uncertain.

Mercury

- Only a small portion of the planet has been observed (before MESSENGER.)
- Is there water ice near Mercury's poles?
- Need to study surface features in detail to understand Mercury's history.

- Why is Mercury's core so large?
- Need to perform a geologic analysis of rocks and soil.
- What are the properties of Mercury's magnetic field?

Venus

- Landers have sent back a few photos of the areas where they landed. Very few of the surface features have seen close-up.
- Need to study the atmosphere and its changes in more detail.
- Need to perform a geologic analysis of rocks and soil.
- Why did Venus become so different from the Earth?
- Could there be life on Venus?

The Moon

- Is there really water ice under the surface near the Moon's poles?
- Need to study rocks in greater detail.
- Are there any resources on the Moon that could be used by human colonists in the future?

Mars

- Why did the water on Mars disappear from the surface? Where did it go?
- Is there any life on Mars today (such as bacteria in ice), or is there any proof of past life?
- Need to study soil and rocks in greater detail.
- Could Mars be changed at some time in the future to be more hospitable to human colonists?

Jupiter

- How can the Great Red Spot (a large storm on Jupiter) have lasted 300 years? What drives the storm?
- Why does Jupiter have an internal energy source?
- Does Jupiter have a solid core?
- Need to understand Jupiter's internal structure better.
- Why are Jupiter's rings so much smaller and fainter than Saturn's?
- Are there more moons yet to be discovered?

Europa

- How much liquid water is under the ice surface?
- Is there life in the water?
- Need to map more of Europa's surface in greater detail.
- Need to understand the behavior of the ice surface better. How thick is the ice? Does water come to the surface, and if so, how?

Saturn

- Need to understand the phenomena in Saturn's atmosphere better.
- Why does Saturn have such magnificent rings? What is their origin?
- Need to understand the behavior of Saturn's rings better.
- Need to understand Saturn's internal structure better.
- Are there more moons yet to be discovered?
- Why does Saturn have an internal energy source?

Titan

- Why is Titan the only moon in the Solar System with a substantial atmosphere?
- The Huygens probe returned photos of only a small part of Titan's surface. What does the rest of the surface look like close-up?
- If Titan's atmosphere is so similar to Earth's early atmosphere, what can we learn about the early Earth by studying Titan?
- Could there be life on Titan even though it is so cold there?

Uranus

- Why does Uranus appear to have fewer features on its atmosphere than the other giant planets? Do more features appear as the seasons change?
- Why are Uranus's rings so much smaller and fainter than Saturn's?
- Need to understand Uranus's internal structure better.
- Why does it not have an internal energy source like the other giant planets?
- What happened when the planet was "knocked over"? Exactly what caused it?
- Are there more moons yet to be discovered?

Neptune

- What drives the strong storms and fast winds on Neptune?
- Why are Neptune's rings so much smaller and fainter than Saturn's?
- Need to understand Neptune's internal structure better.
- Why does Neptune have an internal energy source?
- Are there more moons yet to be discovered?

Pluto

- What does the surface of Pluto look like?

- What is Pluto's composition?
- How does it compare with other dwarf planets?
- What is the composition of Pluto's atmosphere?

Asteroids

- Need to explore more asteroids to see how they compare with each other.
- Need to study composition to provide more clues to the formation of the Solar System.
- What resources are there on asteroids that could be used by human prospectors in the future?

Comets

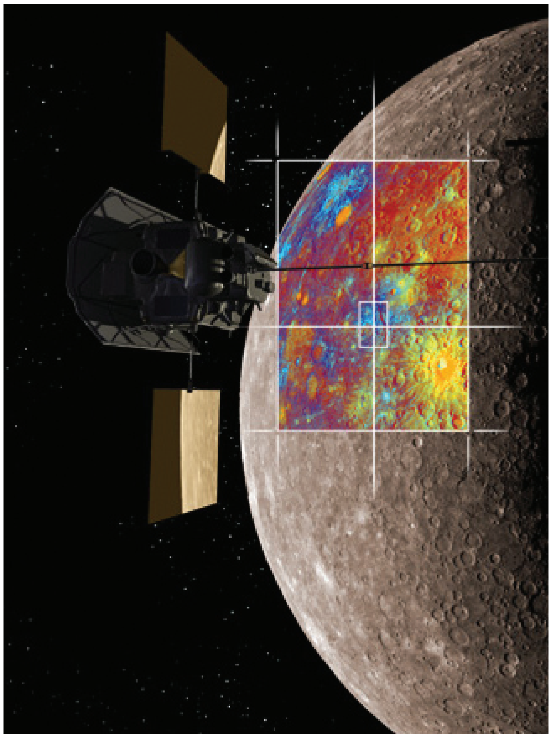
- Need to understand the structure of the comets better, especially the nucleus.
- Need to explore more comets to see how they compare with each other and what they together can tell us about the conditions in the early Solar System.
- What resources are there on comets that could be used by human prospectors in the future?

Kuiper Belt Objects

- What do these objects look like close-up?
- Are there many objects that could be classified as dwarf planets?
- How do these objects compare with Pluto?
- Are there many different kinds of Kuiper Belt Objects; how do they differ in their properties?

The answers to the rest of the worksheet will vary. The main idea of this activity is to get students to understand the detailed planning that is needed to send a spacecraft to explore another world and the costs and the risks that are associated with the missions.

MESSENGER Mission Information Sheet



MESSENGER is an unmanned U.S. spacecraft that was launched in 2004 and will arrive at the planet Mercury in 2011, though it will not land. Instead, it will make its observations of the planet from orbit. MESSENGER will never return to Earth, but will stay in orbit around Mercury to gather data until sometime in 2012.

MESSENGER is an acronym that stands for "MErcury Surface Space ENvironment, GEochemistry and Ranging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be the second spacecraft ever to study Mercury; in 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. How was the planet formed and how has it changed? Mercury is the only rocky planet besides Earth to have a global magnetic field; what are its properties and origin? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.